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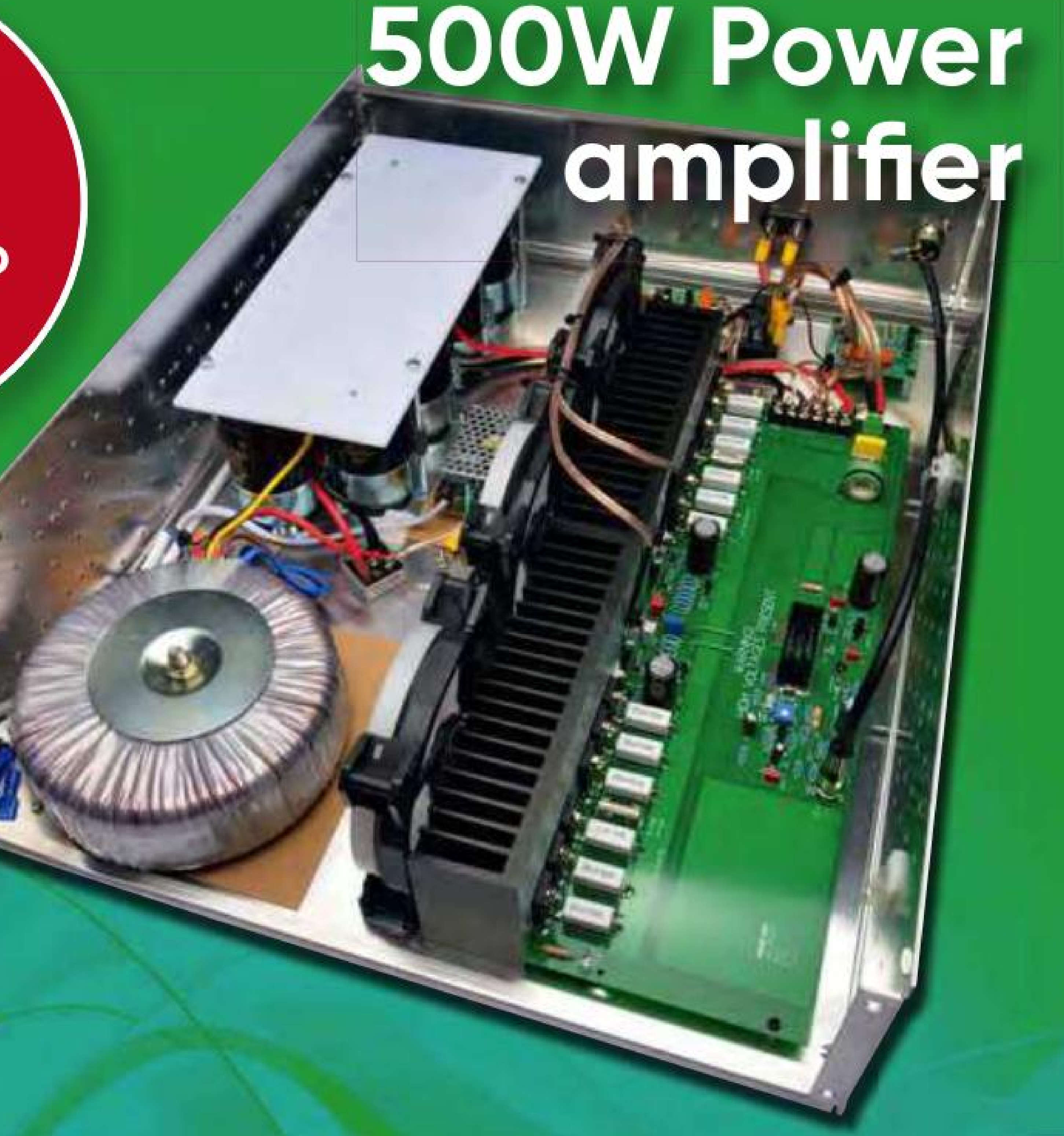

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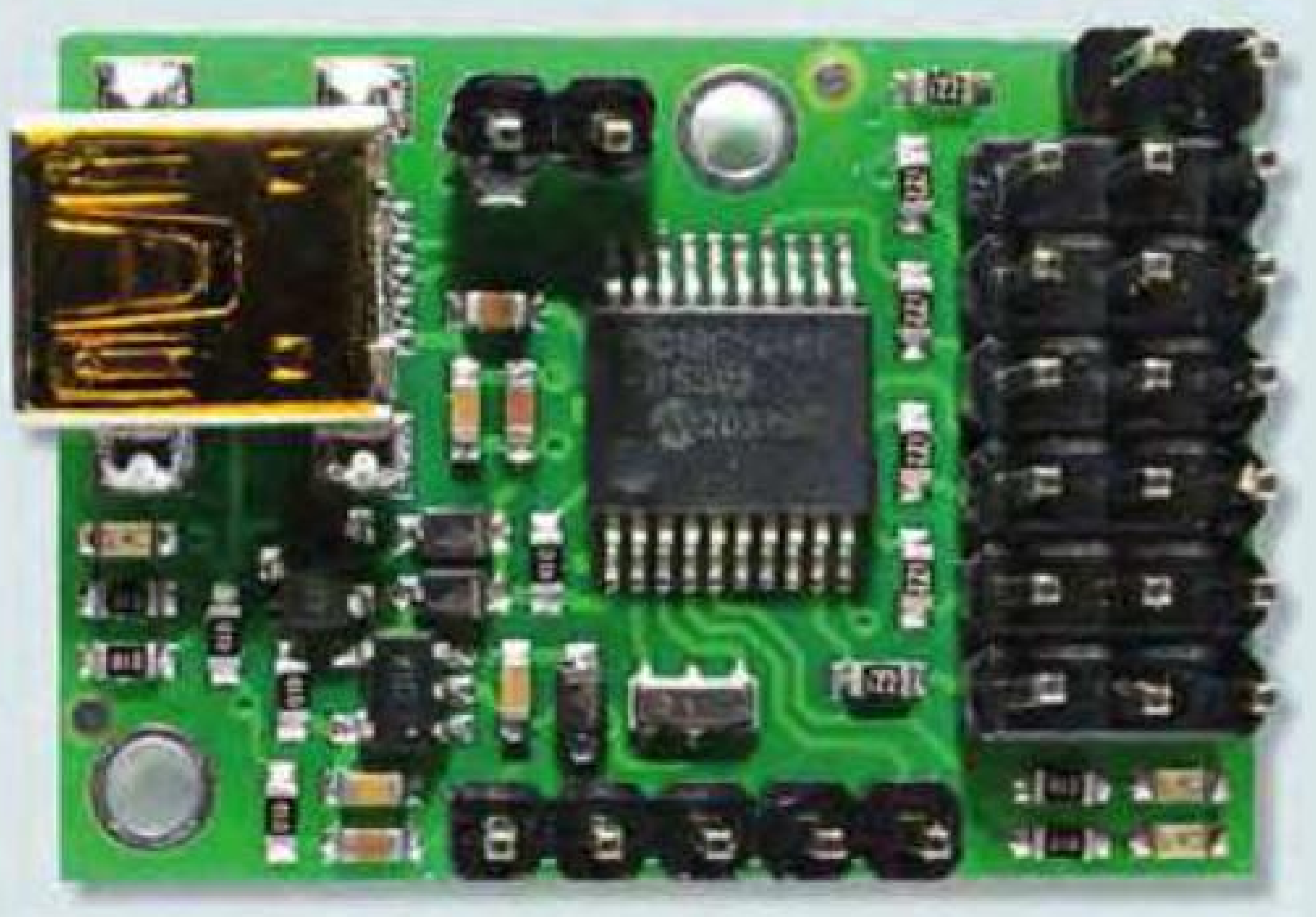

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The June 2023 issue of *Practical Electronics* will be published on Thursday, 4 May 2023 – see page 72.

WIRELESS FOR THE WARRIOR

by LOUIS MEULSTEE

THE DEFINITIVE TECHNICAL HISTORY OF RADIO COMMUNICATION EQUIPMENT IN THE BRITISH ARMY

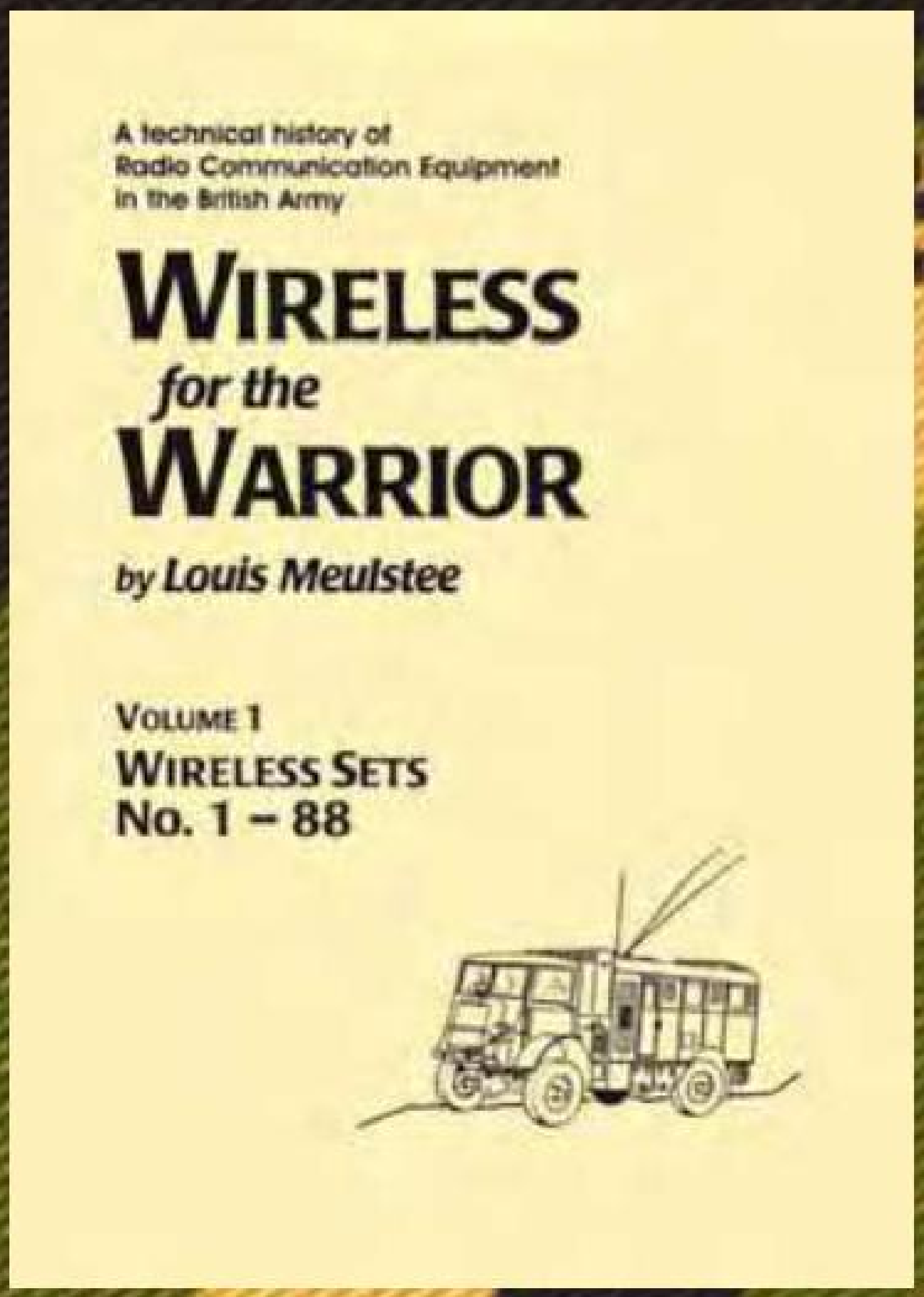
The *Wireless for the Warrior* books are a source of reference for the history and development of radio communication equipment used by the British Army from the very early days of wireless up to the 1960s.

The books are very detailed and include circuit diagrams, technical specifications and alignment data, technical development history, complete station lists and vehicle fitting instructions.

Volume 1 and *Volume 2* cover transmitters and transceivers used between 1932-1948. An era that starts with positive steps taken to formulate and develop a new series of wireless sets that offered great improvements over obsolete World War I pattern equipment. The other end of this timeframe saw the introduction of VHF FM and hermetically sealed equipment.

Volume 3 covers army receivers from 1932 to the late 1960s. The book not only describes receivers specifically designed for the British Army, but also the Royal Navy and RAF. Also covered: special receivers, direction finding receivers, Canadian and Australian Army receivers, commercial receivers adopted by the Army, and Army Welfare broadcast receivers.

Volume 4 covers clandestine, agent or 'spy' radio equipment, sets which were used by special forces, partisans, resistance, 'stay behind' organisations, Australian Coast Watchers and the diplomatic service. Plus, selected associated power sources, RDF and intercept receivers, bugs and radar beacons.



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in the British Army

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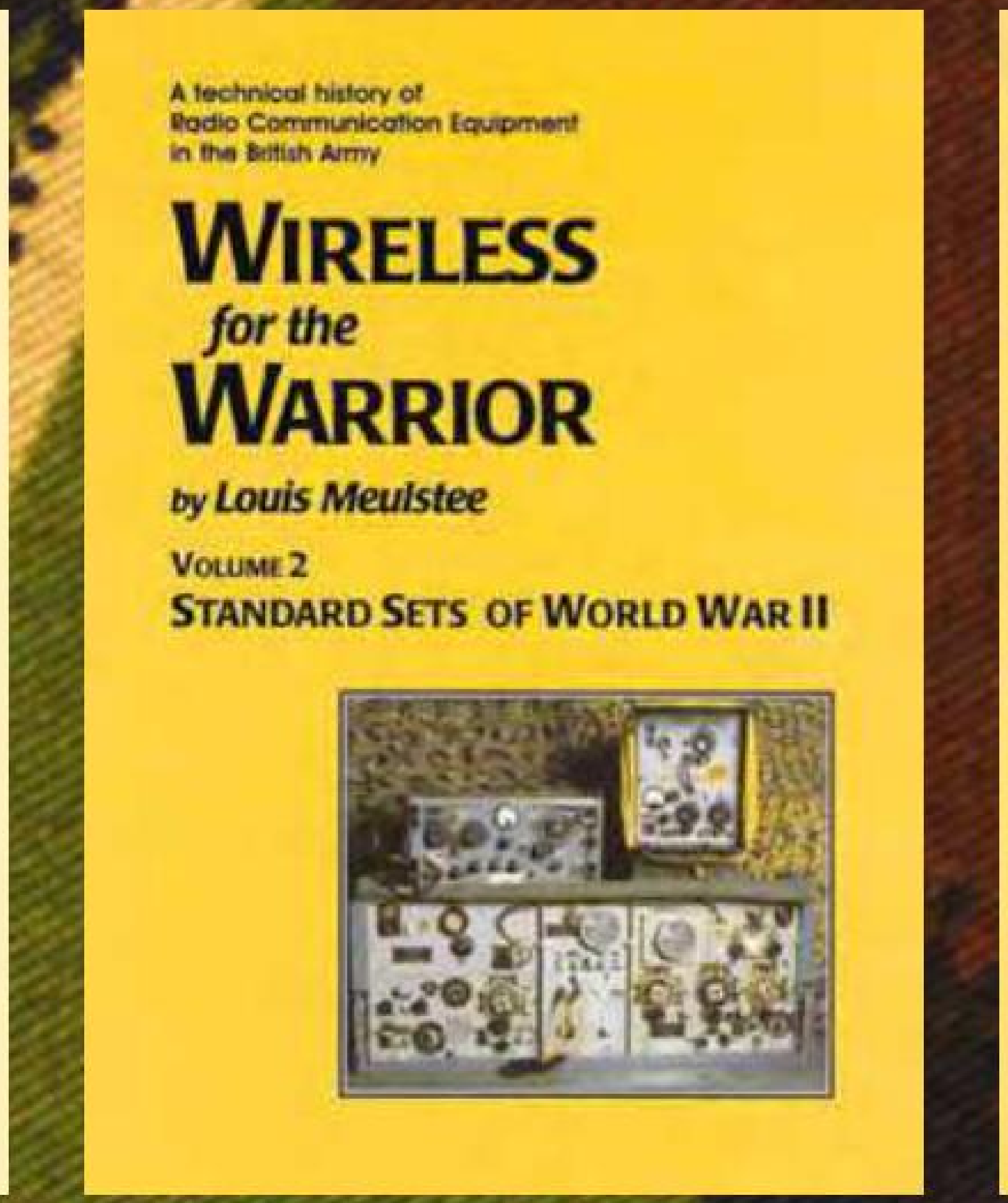

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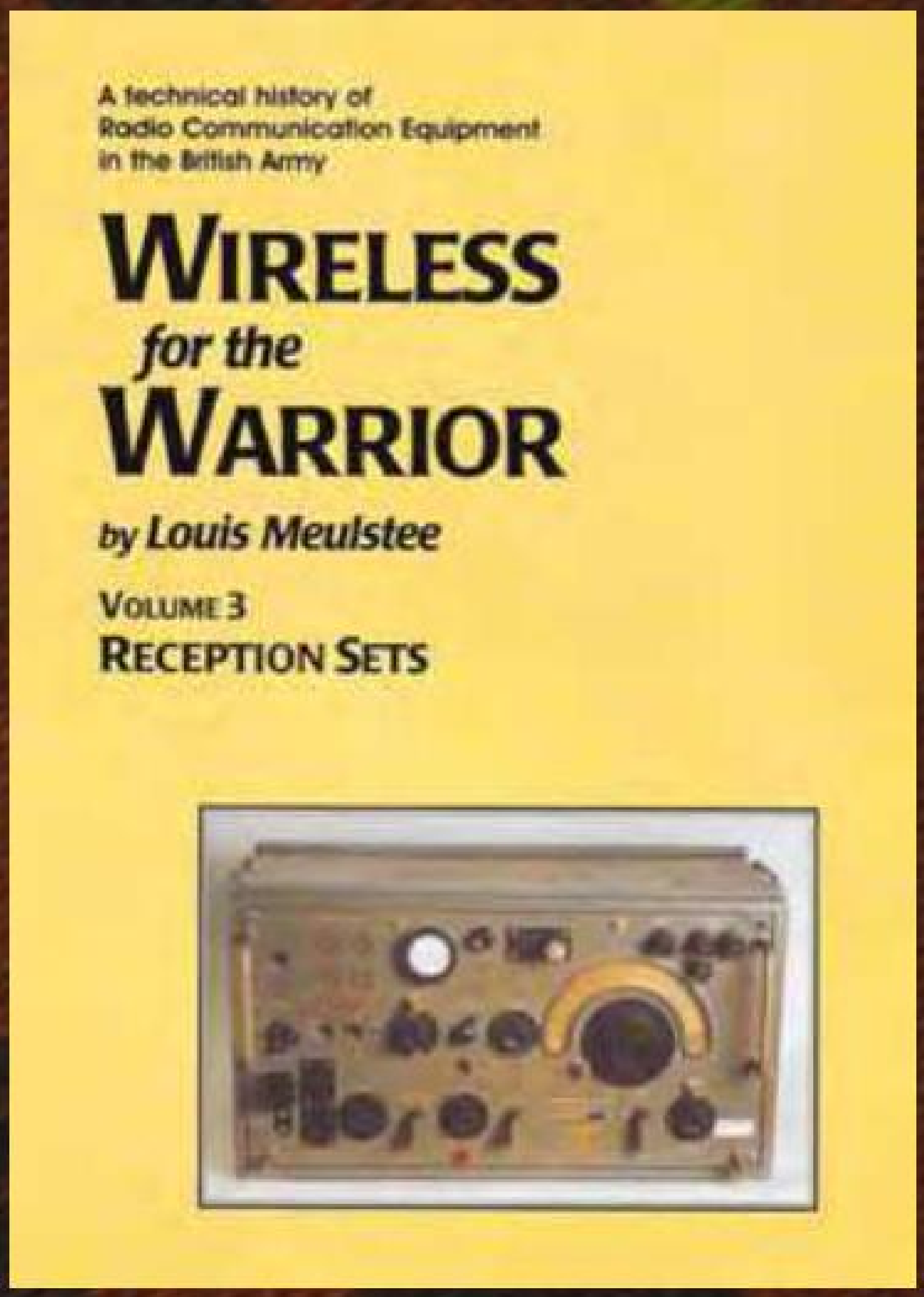

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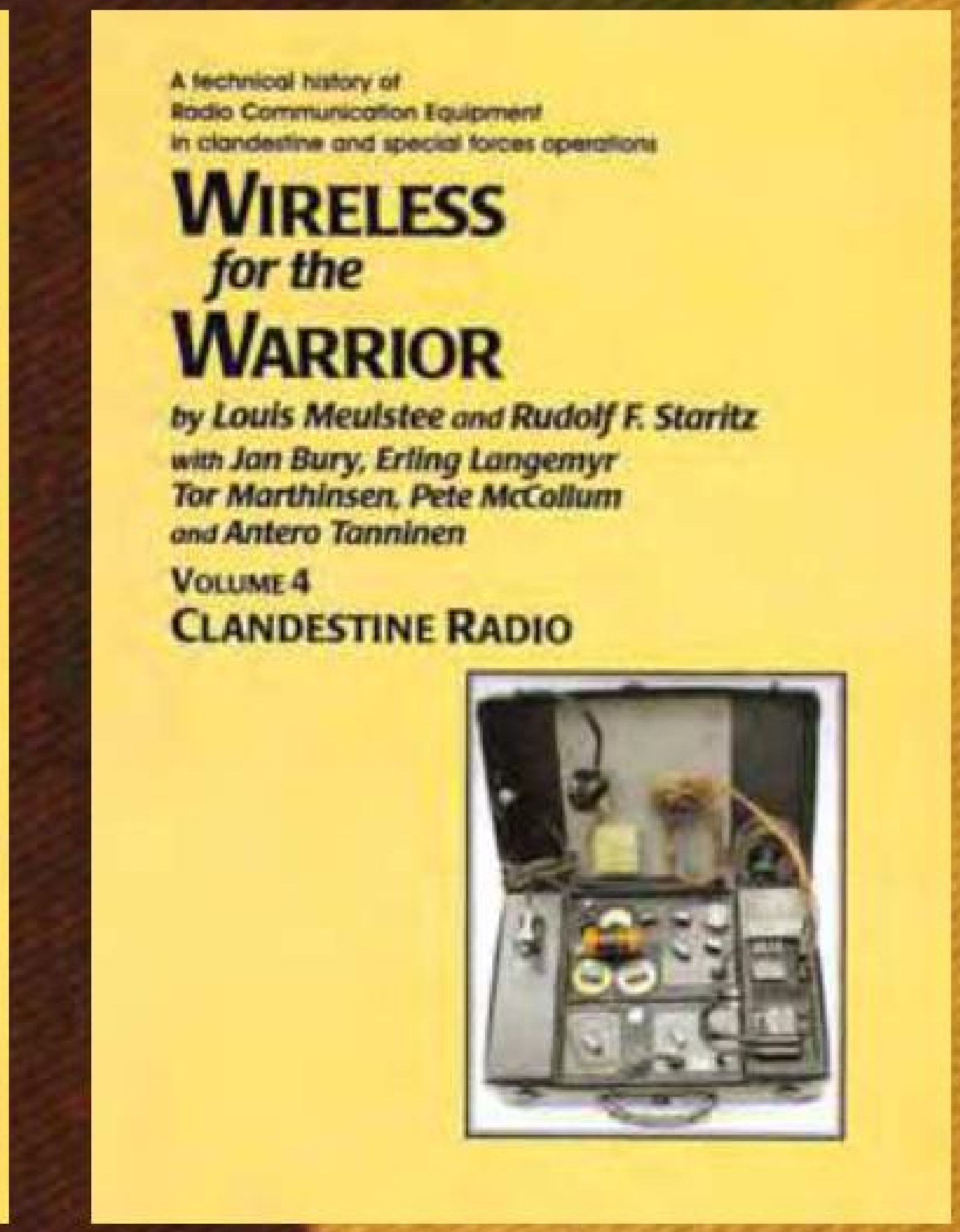

A technical history of
Radio Communication Equipment
in clandestine and special forces operations

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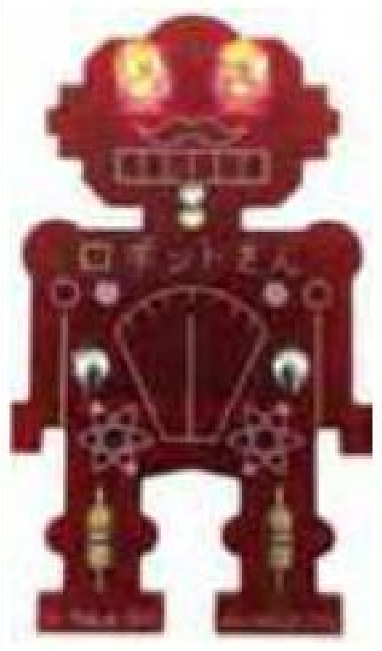

A fun, wearable electronic gadget that you can pin to your clothes. Easy to solder beginners kit. Two flashing bicolour LEDs resemble the eyes. 65 x 40 x 15 mm. CR2032 battery powered (not included).
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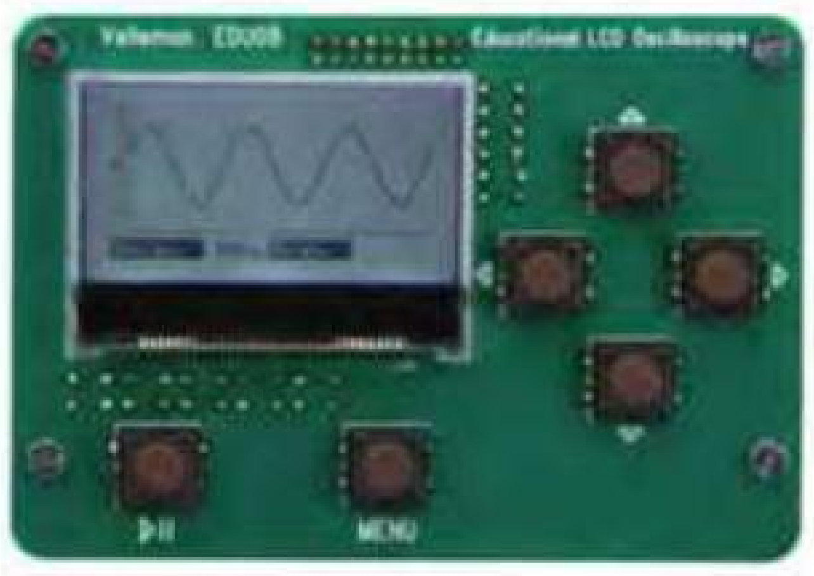

Build your own LCD oscilloscope with this exciting new kit. Learn how to read signals. See the electronic signals you learn about displayed on your own LCD oscilloscope. Despite the low cost, this oscilloscope kit has a lot of features found on expensive units like signal markers, frequency, dB, true RMS readouts and more. A powerful auto-setup function will get you going in a flash!
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1 Buckingham Road **Fax** 01202 843233
Brighton **Email** pe@electronpublishing.com
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Advertisement offices
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Spring is here at last!

The sun is out, the grass is green and it's time to welcome you to the first springtime issue of *Practical Electronic*s magazine. This month, we bring you the latest news on EVs and power generation, fun-to-build projects, insights into learning to use the Arduino, the perils of using op amps as comparators. how to get up and running with RC servo motors and much more.

Turning to this issue's projects, we have our usual, generous helping of exciting circuits for you to build. First up is *Part 2* of the impressive *500W Amplifier* we started last month. Next, a *Precision AM-FM DDS Signal Generator* and last, but not least, an update to our very popular *SMD Test Tweezers*. The latter uses the same fundamental hardware as the October project, but swaps out the microcontroller with a newer, more powerful PIC that can accommodate expanded software. If you liked the first version then you'll love the second one!

Is this me or a computer?

Thanks to recent advances in AI, this is an increasingly important question. Unable to resist the hype, I signed up for a trial run of ChatGPT – the latest AI 'chatbot' to hit the news. To be honest, I really didn't know what to expect. I tried asking it some fairly straightforward, but varied questions just to see what it came up with. 'What is a Laplace Transform?', 'How can I remember my dreams?' and, with a nod to this month's *Circuit Surgery*, 'Do op amps make good comparators?'.

I was impressed. The answers were concise, accurate, written in proper English and – as far as I can tell – not just regurgitated from a Wikipedia page. I then tried a more challenging question: 'Can you write 200 words for the editorial in a hobby electronics magazine?' What returned was a little bland, but by no means generic. Drop in a few key words relating to 500W Amps or a PicoMite and it would be a pretty convincing piece of work. In short, this is an impressive technology that everyone should try: **https://openai.com/blog/chatgpt**

I finished off my first AI session with, 'Who is Matthew Pulzer?' The answer came back: 'I couldn't find any notable public figure or known person with the name Matthew Pulzer. It's possible that Matthew Pulzer is relatively unknown.' Serves me right for asking, but I can't argue with the answer!

Matt Pulzer
Publisher

Prophecy can be perplexing

Techno Talk

Max the Magnificent

Many of the technological discoveries we once found exciting are now lucky if they can elicit a 'Meh!' But what about the possibility of teleportation, the ability to speed up, slow down, or reverse time, or the capability to extract free energy from a quantum vacuum?

A popular Nostradamus quote goes something like, 'Predicting things is difficult, especially if it involves the future'. What? You thought Mark Twain said that? Well, according to *Quote Investigator*, it's been attributed to everyone from Niels Bohr to Yogi Berra: **https://bit.ly/2D0jiSw**

Whoever said it first, this sentiment is spot on. When I graduated from university in 1980, there was no way I could have predicted the far future we now call the present. I mean to say… the Internet, Bluetooth, Wi-Fi, GPS, and MEMS sensors, all coming together to realise smart things in the form of phones, buildings, cities and even watches, for goodness' sake. And then there are robots and cobots (collaborative robots) along with machine vision, artificial intelligence (AI) and machine learning (ML) that actually works, and… the list goes on.

As I mentioned in my previous column, I've been immersed in science fiction since I was a sprog. When I was young and foolish, I truly believed all the technologies I read about were just around the corner. As I grew older and wiser (and balder and sadder), I came to realise that the chances were slight that many of these technologies would ever see the light of day. So, you can only imagine my excitement to discover that, in many cases, those fantastic futures might arrive sooner than expected.

Let's not chat!

You've probably noticed that AI-based tools are currently sprouting up like metaphorical mushrooms. In addition to AI chat and search tools, there are AI art generators, AI writing tools, AI content summarisers, AI speech-to-text transcribers, AI visual editors and AI audio tools, to name but a few.

I bet you think I'm going to chat about *ChatGPT* – see: **https://bit.ly/3JaHyQH** – if so, you'd be wrong. Even though a friend did ask it to, 'Explain semiconductor technology in the style of Clive (Max) Maxfield,' I'm going to restrain myself from discussing the scary results.

However, I did recently use an art generator called *Stable Diffusion Online* (see: **https://bit.ly/3LeUYxJ**). I asked it for 'A pencil sketch of two little boys in boots and shorts using shovels to dig a hole in the back yard.' Only seconds later, I was the proud possessor of an awesome image.

Also, I just tried using *Whisper* to transcribe the audio recording of a customer call into a text file. This literally saved me a couple of hours of wading through the video and making notes by hand – see: **https://bit.ly/3mKIV1f**

Interested in learning more? *Fast Company* provides a wonderful overview of 33 different AI tools you can try yourself for free: **https://bit.ly/3YyYd6t**

Ew! Sticky!

Do you remember the 'before times' prior to the COVID-19 pandemic when we didn't give a second thought to being in a crowded room packed with strangers, shaking hands, or using doorhandles in public places? These days, by comparison, the simple act of using the pump at a petrol station is 'fraught with danger'.

Although they're relatively new, there's nothing revolutionary about the idea of self-cleaning germicidal door handles (**https://go.nasa.gov/3yvwEjO**). But what about touch screens on electronic devices? In addition to the ickiness associated with touching public products, have you looked at your smartphone or tablet computer screen recently? If you do, holding it up to the light, you may well find yourself exclaiming 'Ew! Sticky!'

Happily, the days of sticky screens may soon be gone. I just saw an article on *New Atlas* telling how General Motors (GM) has patented self-cleaning touchscreens that erase oily fingerprints along with all other signs of your presence overnight: **https://bit.ly/3J4TBPL**

In addition to the usual red, green, blue (RGB) pixels, GM proposes to add a fourth ultraviolet (U) pixel type. Meanwhile, the surface of the screen will have an additional transparent coating of a metal-oxide-based catalyst like titanium dioxide. The UV would be activated when the equipment was inactive (like in the middle of the night) resulting in a sparklingly clean and sterile screen.

The Gods Themselves

Everything we've discussed this far is 'small potatoes,' as it were. What about antigravity, spaceships with hyperdrive engines, teleportation, and things of that ilk? On the one hand, it's easy to say that these things are impossible because they defy known physics, but the physics we know and love today was inconceivable not-so-long ago.

As the American physicist Albert Michelson said in 1894, 'The more important fundamental laws and facts of physical science have all been discovered…' This was just three years before the British physicist JJ Thomson discovered the electron.

In 1972, Isaac Asimov published a science fiction novel, *The Gods Themselves*. In a crunchy nutshell, aliens in a parallel universe with different physical laws establish communication with us. They are seeking to exchange matter and exploit the differences between our respective physical laws to provide us both with a source of energy. What they don't tell us is that this exchange will cause our sun to go supernova (thereby giving them all the energy they desire). Fortunately, we detect the problem and determine the solution, which is for us to start simultaneously exchanging matter with a third universe whose physical laws cancel out the instability caused by the first. And then things start to get complicated...

These are just stories, right? Of course, they are. It's barely worth noting that, just a few years ago, Chinese researchers demonstrated the ability to transport photons from the ground to a satellite orbiting 300 miles in space, see: **https://bit.ly/403IXj7**

How about the fact that physicists can speed up, slow down and even reverse the flow of time within a quantum system (**https://bit.ly/3ZXoegB**)? And, just a few days ago as I pen these words, I read how – using quantum mechanics – it's possible to extract energy from a vacuum: **https://bit.ly/3mKGD24**

All I know is that I'm more than ready to take possession of my self-powering antigravity flying car with the optimal teleportation feature.

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Practical Electronics is offering its readers the chance to win a Microchip ATtiny817 Xplained Pro (ATTINY817-XPRO) – and even if you don’t win, receive a 15%-off voucher, plus free shipping for one of these products.

The ATtiny817 Xplained Pro evaluation kit is a hardware platform for evaluating the tinyAVR microcontrollers (ATtiny817, ATtiny816, ATtiny814,ATtiny417). The evaluation kit comes with a fully integrated debugger that provides seamless integration with Atmel Studio.

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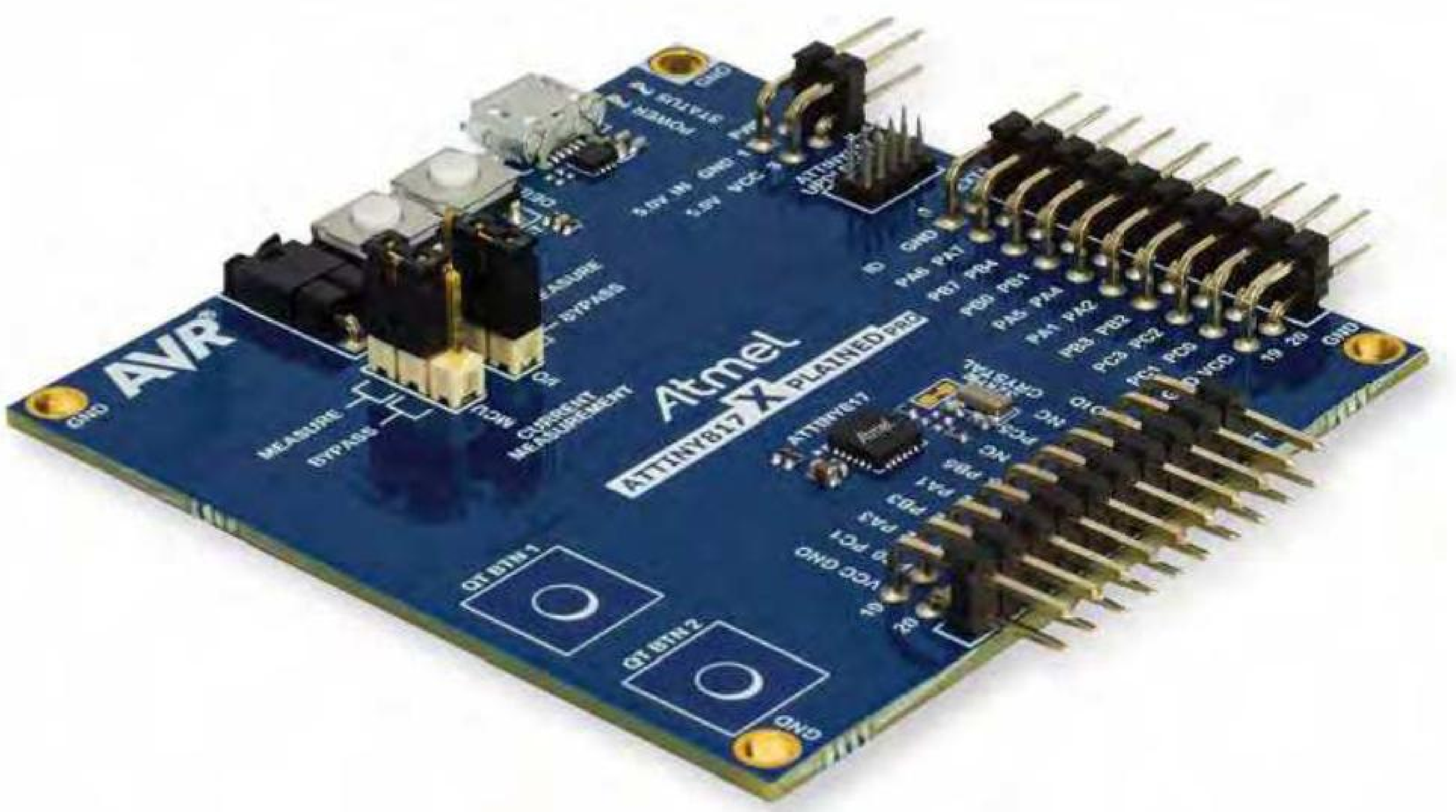

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Microchip ATtiny817 Xplained Pro

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December 2022 winner

Luke Jarvis

He won a PIC32CX-BZ2 and WBZ451 Curiosity Development Board

The **Fox** Report

Barry Fox's technology column

Cinema's insatiable appetite for 'versions'

Hats off to movie industry trade body SMPTE (the Society of Motion Picture and Television Engineers). It does a very good job of educating movie and television engineers. The enterprising UK branch recently held two first-class sessions, which I was lucky enough to attend.

For one of them, SMPTE gained access to the National Physical Laboratory in Teddington, to learn more about time – more next month.

For the other event, SMPTE took over the Dolby Screening Room in Soho Square to show Disney's *Avatar: The Way of Water* in immersive audio, high frame rate, and high dynamic range 3D. Carly Brown, Disney's Director of Motion Picture Operations, and Rich Welsh, Deluxe's SVP of Innovation, talked ahead of the screening about the mind boggling multitude of sound and picture formats needed for release to different types and grades of cinemas worldwide, ranging from high-end Dolby venues (such as the Leicester Square Odeon or the new Battersea Power Station cinema) to bog-standard flea pits and local multi-purpose halls.

Multiple versions

According to Brown and Welsh, run-of-the-mill movies are released in around 100 versions, with 'bigger' titles hitting 500. But *Avatar: The Way of Water* (*AWOW*), ideally needed 5000 versions, compromised down to a final 1065 versions, partly because it's in 3D (which involves different projection systems needing different brightness and colour gradings) and partly because movie maker James Cameron wanted multiple aspect ratios to stop cinemas with different screen sizes projecting pictures with black masked bars and borders. There are 27 different aspect ratio versions of *AWOW*.

The sound options range from simple stereo and surround to Atmos immersive, with subtitles in 51 languages and 28 language dubs.

Whereas most cinemas project at 24 frames per second (fps), a few (Dolby) cinemas can handle 48 fps. The 24 fps versions of *AWOW* were down converted from 48 fps.

In fact, *AWOW* uses a mix of material created at 24fps and 48 fps. This explains why keen eyes will spot 24 fps motion artefacts (judder) in some action sequences, even when the movie is playing at 48 fps.

The subtitles were originated in 3D and down converted to 2D for the 2D cinema versions. The 3D titles hover in unusual areas of the screen, at different depths.

10 quadrillion bytes

The post-production engineers handling all this work were split between New Zealand and California, with a database of 10PB (one petabyte (PB) equals one million gigabytes) of uncompressed audio and video and metadata, representing 381 million picture frames. This was moved across the world by Amazon's Web Cloud service, which needed radical tweaking by *AWOW* engineers to make it fast enough. The data was physically moved by undersea cables, using 'dual wet routes'; a matched pair of 10GB fibre 'pipes'. In this way, if a trawler drags up a cable and breaks it, the data keeps on streaming.

In all, 3500 hours of movie material was cut to the final release length of 3 hours 12 minutes. To achieve all this, movie engineering companies that normally compete ended up working together to get the job done. The credits at the end of the movie are as long as a short film. Even James Cameron was moved to admit: 'I've never worked like this before, and I never want to again'.

The Dolby screening room in London is classed as a 'grading theatre' and is thus permitted to screen movies in pitch black, without any of the emergency lighting or Exit signs which public cinemas must provide. It's a unique way to watch a movie and reminds how much ambient light pollutes all other cinemas.

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Amazon's Ring camera has an annoying habit of auto-updating itself to death.

Likewise, the Dolby screening room can use the Dolby 3D system, which was developed by German company Infitec, and is less fatiguing than other systems, but not commercially viable. The spectacles (which filter slightly different red, green and blue spectra for the left and right eye views) cost at least £25 a pair and are thus too expensive to risk losing to light-fingered customers.

Was all Cameron's work worthwhile? Everyone will have their own opinion, but *AWOW* is a remarkable technical achievement on all counts. As a movie, I find it far too long and too loud, with endless bang, whoosh, boom and ratatat audio effects for interminable battle scenes. There are also some very distressing sea creature harpoon hunting sequences that remind of the infamous 1956 *Moby Dick* movie with Gregory Peck.

But for those who enjoy Marvel-Comic-style blockbusters, which play like a computer game with no pause control, *AWOW* will hugely appeal. Reportedly, it has earned more than $2.2bn worldwide. It was nominated for four Oscars, including best picture and won the Best Visual Effects category.

Helplines Coda

Amazon is a clever company with mould-breaking ideas, but perhaps not always as clever as it thinks.

I recently started to use a Ring CCTV camera that had being lying in my drawer for a while. It worked for around half an hour and then decided to download itself a firmware update. The update 'bricked' the camera. It was stone dead, showing no lights or other signs of life.

I followed all Ring's recommended fault-fixing steps, including fully charging the battery, removing and replacing the battery and pressing the reset button for short and long periods.

A quick Google-check showed that other Ring camera users had experienced exactly the same problem; a forced update that bricked the device.

Just for the heck of it I called the Ring Help line, which is run by Amazon who bought the Ring company. As I feared, I was compelled to repeat all the same fault-fixing steps while the helper (in South Africa) religiously followed her script and made side-calls for more help from more senior helpers.

After an hour of laboriously achieving absolutely nothing Amazon insisted that I try one last fix. I had to sit by the dead and disconnected device while Amazon tried to force an update over the Internet. I tried politely to question the logic behind this powerful magic. If a stone dead device isn't connected to anything, how can it receive anything? But the helpers insisted on trying.

I then began to doubt my sanity and wonder whether the clever boffins at Amazon might perhaps be selling super-clever cameras that can play dead but actually respond remotely, much as the Pegasus software from Israeli company NSO lets security services access apparently dead camera phones. If so, that would be a real story!

But sadly, or fortunately, this failed too. Amazon-Ring's Helpers finally had to acknowledge that the dead device wasn't responding to the firmware that Amazon was optimistically pushing into the ether.

Like all the other users complaining about their bricked Ring cameras, I have now been offered a 30% discount off the price of a new Ring device to risk being bricked.

Whether I contest or take up the offer is a whole other story which will probably be too long and boring to recount. But owners of Amazon Ring cameras can rest easier in their beds, knowing that they are not being silently surveilled.

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Net Work

Alan Winstanley

This month's column brings the latest electric vehicle trends and new EV brands about to launch in Britain, with updates on the power generation front and, of course, the latest from the LEO satellite broadband sector.

Previous Net Work columns brought news of Britain's electric vehicle sector as the lurch towards car electrification gathers pace. The UK's Society of Motor Manufacturers and Traders (SMMT) reports that 52% of all new car registrations in February were battery-powered (BEV), hybrid (HEV), mild hybrid (MHEV) or plug-in hybrid (PHEV). Those BEVs represented 16.5% of all UK February car registrations. Even so, 48% of new cars registered in February were still petrol (gas) or diesel – a far higher proportion than in, say, EV-friendly Norway – but there was of course no reference to *used* car sales, whether fossil-fuelled or electrically propelled. Despite the interest in new EV cars, the high cost and practical challenges of running them puts them well beyond the reach of many motorists struggling in today's financial climate.

However, the signs are that interest in buying used EVs has cooled dramatically in Britain: wary buyers, already feeling the pinch from the rising cost of living and energy costs, are deterred by the dearth of EV charging points, worries about range anxiety and nagging doubts about becoming lumbered with yesterday's outdated (or worn out) battery technology. As used EVs are gradually 'returning to the market', some secondhand EV models are suffering 'incredibly large drops' in value, says car dealer journal *Automotive Management*. They report that the lack of interest in buying used EV cars is such that some dealerships have stopped stocking them altogether, in order to avoid getting stuck with large inventories of rapidly depreciating electric cars that simply aren't selling.

Highlighted is the Tesla Model 3, which has dropped over 33% on average in the past four months, and Tesla also skewed the market by slashing new car prices by up to 20% earlier this year, as supply finally started to exceed demand. Semiconductor shortages and supply chain problems didn't help EV sales either, so consequently there is still a keen interest in buying sensibly priced petrol cars instead. It seems there is plenty of life left in older petrol cars before sales of new ones are banned altogether. Maybe those used EVs will be sold off at bargain basement prices in coming months.

The Atto 3 is BYD's (Build Your Dream) first EV to launch in Britain, featuring a futuristic interior and 'Blade' battery.

Who's in charge?

Britain continues to drag its heels over the supply of EV charging points. New British housing stock is supposed to include an EV charging point, but as one web forum poster pointed out, 'if the local electricity substation that feeds your street has a 400A fuse, and every house has at least one 32A charger, then you do the maths. They can't even roll out smart meters for every house and that's cost more than £12bn so far, and is far from complete... I understood that the electrical load of a new housing estate averages eight amps per property, and now they want to add 32A for one EV on top of changing your gas central heating boiler to a heat pump,' the poster mused.

In the January 2022 issue I mentioned a possible charging solution for EV owners in the shape of a semi-portable battery pack on wheels, called the ZipCharge Go. This well-publicised powerbank was being developed for 'topping up' EVs in the street or car park – the idea was due to launch some time this year, but I now understand that the ZipCharge Go never made it beyond the prototype stage. This illustrates the typical vagaries of this fast-moving tech sector.

At least British EV owners are not alone in suffering practical problems of EV ownership. An American EV owner recently posted on Reddit: 'Was at the Electrify America station in Indiana yesterday. In a blizzard. With 30 miles of range and about 75 miles to drive. Station had eight chargers. Only ONE was working and it was in use. The EA call centre was useless. Took hours to get a charge when it should have taken 20 minutes. Until this gets figured out, electric cars will be limited, period.' Sounds all too familiar.

Blade Runner

Listed in nearly 74,500 new February registrations were exactly 13 (thirteen) GWM Ora £32,000+ electric mini cars, the cute Chinese EV previously described in *Net Work*. There are yet more Chinese EV brands, almost too many to follow, heading our way across Northern Europe, starting with BYD – an acronym for 'Build Your Dreams'. BYD is barely 20 years old and may be unfamiliar to most readers, but BYD is a huge Chinese conglomerate that manufactures semiconductors and batteries as well as solar arrays, energy storage systems, EV chargers and electric buses. Cars made by subsidiary BYD Auto will arrive in British

The Atto 3 cabin is 'built with the concept of sports and fitness' with a 'trendy and avant-garde design', BYD says. Traditional motorists might not agree.

showrooms this year, starting with the attractive BYD Atto 3 compact SUV.

Of particular interest is BYD's 'Blade' lithium-iron-phosphate battery that they claim is among the safest in the world. BYD reckons that the pressure to improve car cruising range had forced battery makers to pursue an increase in battery energy density over safety considerations. BYD's Blade battery uses a unique cell construction, which they stated withstood nail puncture tests and neither overheated nor produced smoke. When damaged, ordinary Li-Ion batteries have a tendency to thermally runaway and are nearly impossible to extinguish once they start to melt down – often exploding – as graphically described in previous *Net Work* columns. Other Blade safety distinctions include having a high starting temperature for exothermic reactions, slow heat release and low heat generation, as well as an ability to not release oxygen during breakdowns or easily catch fire.

BYD adds that their smart technology allows for 'bi-directional EV charging'. Suitably equipped vehicles could charge overnight at off-peak times when energy demand is low, and become a powerbank to feed energy back into the electricity grid when demand is high. A year ago, in the May 2022 issue, I mentioned this V2G or V2H (Vehicle to Grid/ Home) technology but this is barely at a developmental stage here in Britain. In comparison, BYD has offered DTG (Direct to Grid) charging since 2015 when its conventional-looking 'e6' car was first launched in the US – it was the only car on sale at that time with V2G included as standard.

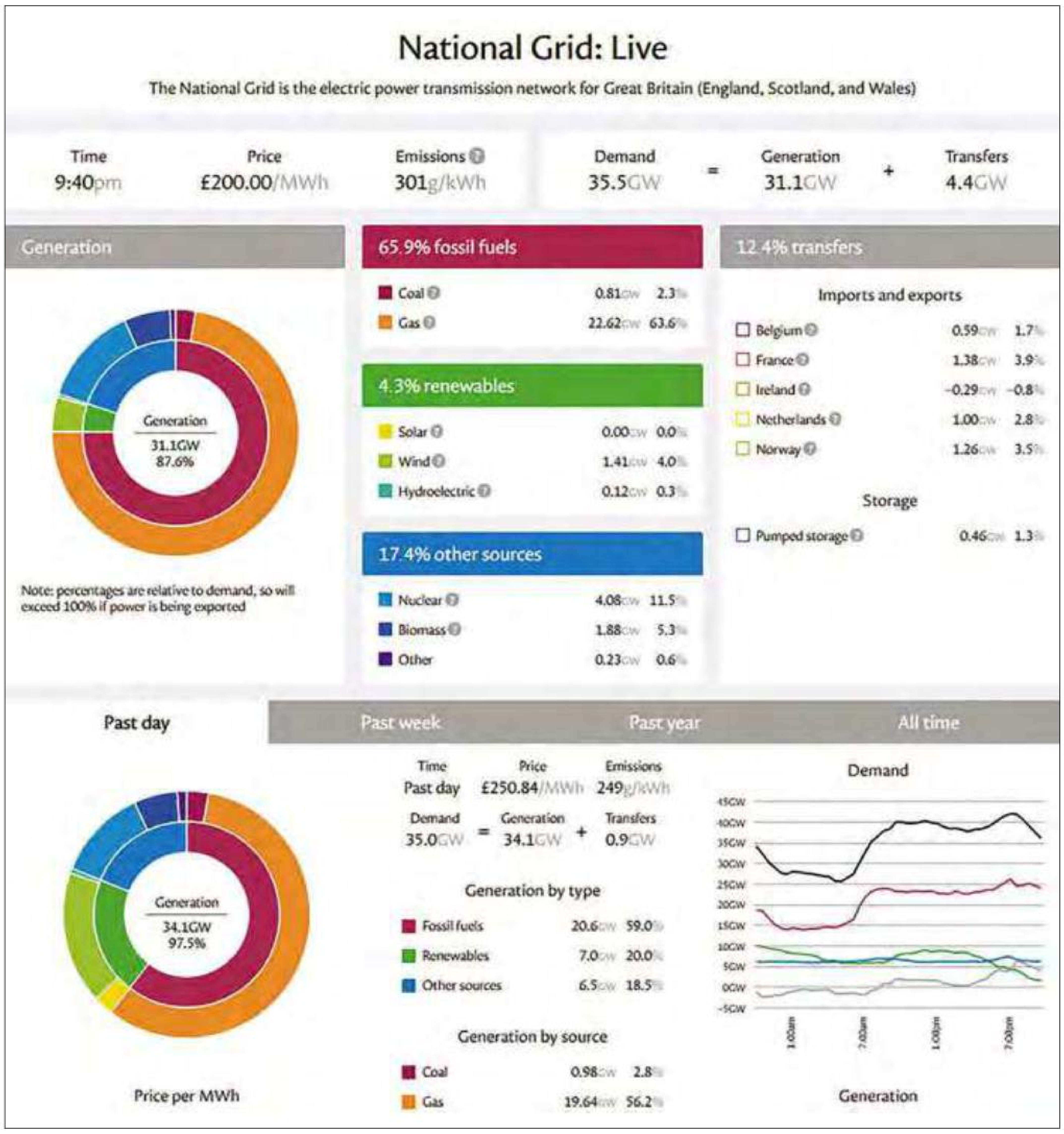
As things turned out, BYD arrived in the UK well over a decade ago, floating its 'e6' potentially as a taxi, but the Chinese firm has kept a low profile ever since – until now. As well as in the UK (eg, Arnold Laver dealerships), dealers for BYD electric cars have been signed up across Europe. Traditionalists who prefer to use tactile knobs and switches might not adapt so well to the touchscreen way of doing things in an electric vehicle, but the BYD Atto 3 has a stylish interior dash that's 'built with the concept of sports and fitness' with a 'trendy and avant-garde design' they say, so its target market is clear to see. BYD is presently slugging it out with Tesla over pricing, but the BYD Atto 3 is part of a phalanx of futuristic-looking electric vehicle brands, including XPeng, Fisker and Nio that may eventually become familiar sights on Britain's roads. European drivers will also see an extremely sleek executive car and SUV from BYD. The Atto 3 is expected to cost around £35,000. For more details, see: **www.byd.com/eu/car/atto3**

Energy for tomorrow

Despite earlier dire predictions of possible power cuts, the UK seems to be weathering the winter storms well, at least as far as energy consumption is concerned. In March, National Grid ESO (the UK electricity system operator) tweeted that an electricity margin notice (EMN) had been issued to the market for one day, which meant that Britain's last remaining coal-fired power stations were 'warmed up' just in case they might be needed to top up the supply. It takes time and money to get a coal-fired station up to speed, and environmentalists were hopping mad at the thought of it, but, thanks to the efforts of all those in our hard-working energy sector, the lights are still on, and life goes on as normal. This time round, smart meter users were not asked to reduce their consumption in return for receiving a small cash bonus.

Software developer Kate Rose Morley has coded a very impressive website that publishes more live National Grid data than I know what to do with – it's available for viewing at: **https://grid.iamkate.com**

Historical trend graphs (under 'Generation') show the gradual total elimination of coal, a steady decline in nuclear and a rise in wind power



National Grid: Live

The National Grid is the electric power transmission network for Great Britain (England, Scotland, and Wales)

Time	Price	Emissions	Demand	=	Generation	+	Transfers
9:40pm	£200.00/MWh	301g/kWh	35.5GW	=	31.1GW	+	4.4GW

Generation

Note: percentages are relative to demand, so will exceed 100% if power is being exported

65.9% fossil fuels

Coal	0.81GW	2.3%
Gas	22.62GW	63.6%

4.3% renewables

Solar	0.00GW	0.0%
Wind	1.41GW	4.0%
Hydroelectric	0.12GW	0.3%

17.4% other sources

Nuclear	4.08GW	11.5%
Biomass	1.88GW	5.3%
Other	0.23GW	0.6%

12.4% transfers

Imports and exports

☐ Belgium	0.59GW	1.7%
☐ France	1.38GW	3.9%
☐ Ireland	-0.29GW	-0.8%
☐ Netherlands	1.00GW	2.8%
☐ Norway	1.26GW	3.5%

Storage

☐ Pumped storage	0.46GW	1.3%

Time	Price	Emissions
Past day	£250.84/MWh	249g/kWh

Demand	=	Generation	+	Transfers
35.0GW	=	34.1GW	+	0.9GW

Generation by type

Fossil fuels	20.6GW	59.0%
Renewables	7.0GW	20.0%
Other sources	6.5GW	18.5%

Generation by source

Coal	0.98GW	2.8%
Gas	19.64GW	56.2%

An impressive data website coded by Kate Rose Morley displays National Grid generation and statistics.

Left: The first of two French-built 500-tonne reactor vessels arrived at the UK's Hinkley Point C nuclear power station in February.

Above: A Russian-built poloidal field coil was successfully delivered to the multinational ITER nuclear fusion pilot plant in France in February.

generation over the past ten years. For a different outlook on the National Grid stats, try the graphs and dials shown on: **www.gridwatch.templar.co.uk**

The Hinkley Point C nuclear power station in Britain is the first new one to be built in 20 years. Sadly, like a number of other key infrastructure projects in Britain, it has suffered delays and construction cost overruns. In February the site received the first of two French-built 500-tonne nuclear reactor vessels, as construction of this 'too-big-to-fail' power station continues with completion expected within five years. Interested readers can find more background on the history and status of Hinkley Point C at: **https://bit.ly/pe-may23-hinkc**

Previously covered in *Net Work*, December 2022, the International Thermonuclear Experimental Reactor (ITER) is an ambitious multi-national effort being built in France to explore the boundaries of nuclear fusion. The ITER tokomak will not however be used to generate electricity for the grid. In February, after a near four-month voyage from St. Petersburg, a giant Russian-made 160-tonne poloidal field coil was successfully delivered to the ITER site, having taken some six years to fabricate. Russia's Rosatom is contributing 400 tonnes of equipment to the ITER project, which has now reached 78% along the road to 'first plasma'.

Space is (still) hard

London-based network operator OneWeb continues to build its constellation of satellites intended to provide Internet access between the North Pole and the 50th parallel. OneWeb uses a number of service providers, including friendly rival SpaceX, to launch small batches of its satellites into LEO.

To digress for a moment, it's funny how a feeling of deja-vu can trigger distant memories: when I hosted the *Ingenuity Unlimited* column of readers' circuit ideas here at *Everyday Practical Electronics* in the 1990s, I received a circuit suggestion for a 4000-series CMOS-based electronic rotary switch from an engineer who worked at the emerging Indian Space Research Organisation (ISRO) Department of Space. It was carefully typed with a dot-matrix printer on tissue-thin paper, which I found in my archives (fortunately, I'm ruthlessly methodical) and our correspondence had always stuck in my mind.

Fast forward 25 years, and in October 2022 a jubilant ISRO launched its new LVM3 (Launch Vehicle Mk. III) rocket from the Satish Dhawan Space Centre in Sriharikota and it successfully placed 36 OneWeb satellites into their intended orbits. The triumph was one of India's biggest ever commercial orders, and the launch can be seen at: **http://bit.ly/3yFSAsn**

OneWeb's constellation of 542 first-generation satellites is nearing completion, and a second launch from India was due to lift off in March.

Following the outbreak of the Ukraine conflict, 36 OneWeb satellites worth some $230m were impounded at the Russian-controlled Baikonur Cosmodrome in Kazakhstan, where presumably they have lain ever since. It's thought that they could now be traded for some badly needed Russian Soyuz stages languishing at the European Spaceport in French Guyana, which is situated in north-eastern South America. Roscosmos pulled the plug on co-operating with the European Space Agency, leaving critical Soyuz rocket parts behind.

The European site accommodates the European Ariane 5 as well as Russian-built Soyuz vehicles, but the ESA continues to develop its long-overdue Ariane 6 launcher which is now slated to launch from French Guyana by the year end. Last year, Arianespace signed a contract with Amazon for 18 flights carrying satellites into LEO for Project Kuiper, Amazon's own satellite-based Internet service that is still seeking regulatory approval. More details are at: **www.arianespace.com** – note that there is no website for Kuiper, although **projectkuiper.com** leads to an enigmatic login page.

Other news

An advanced new fusion energy prototype will be built by Tokamak Energy at the United Kingdom Atomic Energy Authority's (UKAEA) Culham Campus, near Oxford. The compact spherical tokamak, called ST80-HTS, is due for completion by 2026. It will incorporate advanced technologies required for the delivery of sustainable fusion energy, including cutting-edge high temperature superconducting magnets to confine and control the hydrogen fuel, which becomes plasma many times hotter than the sun, they report. Last year, their current ST40 fusion device in Milton Park, Oxfordshire, achieved a 100-million-degrees-Celsius fusion plasma – the highest temperature ever recorded in a compact spherical tokamak, the research centre reported.

The European Union has formulated in record time plans for a new secure satellite communications programme of its own. Called IRISS (or IRIS^2), the Infrastructure for Resilience, Interconnectivity and Security by Satellite may see the development and launch of up to 170 LEO satellites between the years 2025 and 2027. It's also intended to integrate with other EU space programmes such as the Copernicus earth observatory and Galileo satnav, as well as offering secure communications while eliminating Internet dead

India's Space Research Organisation Dept of Space readies a payload of 36 OneWeb satellites for launch into low-earth orbit.

spots in Europe and across the entire African continent.

America's Lockheed Martin has announced plans to build its first satellite factory outside the US in Britain, which will create 2,000 skilled jobs in Britain's booming space sector. The firm states, 'it is serious about having a footprint in the UK and creating UK jobs, as well as developing the UK supply chain.' Lockheed Martin, in partnership with ABL Space Systems, would be among the first companies to support a launch from the SaxaVord Spaceport – one of Britain's new vertical spaceports, currently under construction (see last month).

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So far this week
ivie Bud

The Ivie Bud is a replacement In-Home Display with app, for UK smart meter owners. Check compatibility online.

Japan's first launch of its new H3 rocket on 7 March ended in failure when a self-destruct signal had to be sent to abort the mission, destroying the Advanced Land Observing Satellite-3 payload. The Japan Aerospace Exploration Agency (JAXA) suspects that the second stage failed to ignite – see: **http://bit.ly/3FqcV93**

Space is still hard to do and full of 'anomalies' and 'launch attempts', as JAXA, Virgin Orbit, Skyrora and ABL Space Systems have all recently found.

Green tech company Ivie is selling a replacement or upgrade In-Home Display (IHD) for British smart meter owners. The Ivie Bud costs £49.99 and will work with any energy supplier, they say, but it's necessary to check smart meter compatibility before buying. This can be done online at **https://ivie.co.uk/product/ivie-bud/** and the Ivie app is available from Google Play and the App Store. Alternatively, there's the Loop app (with no IHD) that links to your smart meter, see: **https://loop.homes**

That's all for this month's *Net Work*. Don't forget that the hyperlinks above are ready-made for you to click on in my *Net Work* blog summary at: **www.electronpublishing.com**

See you next month!

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Datron 4708	Autocal Multifunction Standard	POA
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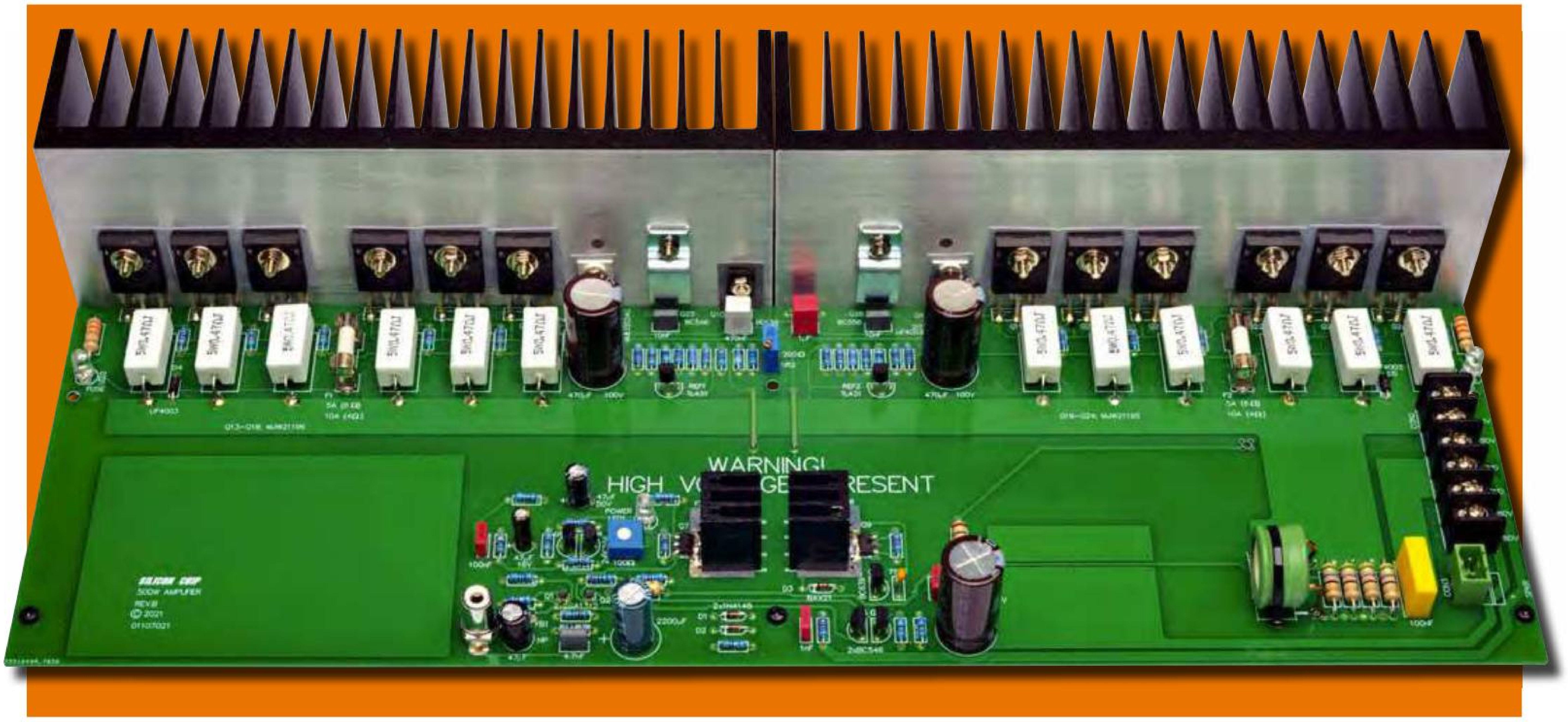
500 WATTS POWER AMPLIFIER

PART 2

BY JOHN CLARKE



Having described our new *500W Amplifier Module* last month, giving its performance details and describing the circuit, we follow on this month with the amplifier construction, beginning with the PCB (Amplifier Module) assembly. Next month, we'll build this into a complete amplifier, along with fan cooling, a speaker protector and a clipping detector.

The 500W Amplifier has four main components: the *Amplifier Module*, its power supply, the *Fan Cooling and Loudspeaker Protector* board and the *Clipping Indicator* board. The last two of those have already been described in the February and April 2023 issues respectively.

This article focuses on the assembly of the *Amplifier Module* – its circuit was described last month. Next month, the final article will detail the power supply, the chassis and the final assembly and wiring, bringing all those parts together.

Now let's move on to building the all-important *Amplifier Module*.

Construction

The *500W Amplifier Module* is built on a double-sided, plated-through PCB coded 01107021 that measures 402 x 124mm. Refer to Fig.6, the parts layout diagram during construction.

Before starting, it's a good idea to inspect the board carefully. This will familiarise you with its layout and reveal any defects (however unlikely that is).

Start construction by fitting transistors Q1 and Q2. These are small SOT-23/TO-236 surface-mounting devices. They are relatively easy to solder due to their widely spaced pins, but you might need the aid of a magnifying glass and strong light if your vision is not perfect.

First, align Q1 onto the pads, holding it with tweezers, and solder one of the pins to the PCB. Check that it is correctly aligned with the other pads, reheating the solder joint to realign if necessary. Then solder the remaining pins. Mount Q2 similarly.

Don't worry if you add so much solder that the joints on these SOT-23 parts look like small silver balls. This is unlikely to cause any problems; we want to joints to be shiny, and adding a bit too much solder is better than not adding enough!

If you feel the need to remove the excess solder, add a little bit of flux paste and touch the join with a clean soldering iron tip.

Now mount the small (¼W or ½W) resistors. Check each value using a digital multimeter set to read ohms before soldering in place. Don't just rely on the colour bands to determine the value, as these can be difficult to read accurately.

Note that there are two pairs of resistors labelled R1 and R2 on the PCB; they don't have associated values. The nominal values required for these resistors (which define the SOA protection curves) are R1 = 35.328kΩ and R2 = 204.8Ω. We can't get these exact values, but there are two ways we can get close.

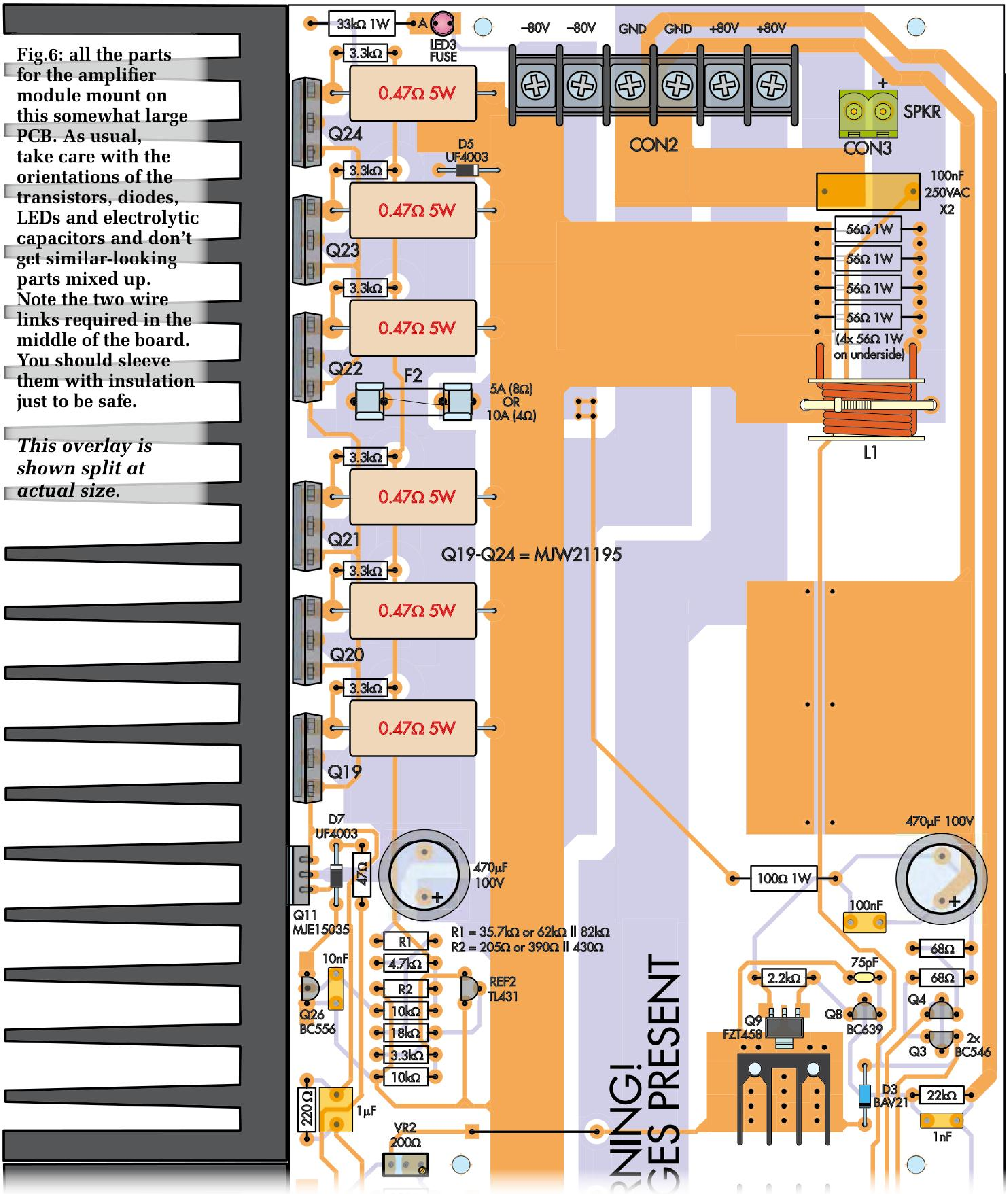

33kΩ 1W
A
LED3
FUSE
3.3kΩ
0.47Ω 5W
Q24
D5
UF4003
Q23
Q22
F2
5A (8Ω)
OR
10A (4Ω)
Q21
Q20
Q19
Q19-Q24 = MJW21195
–80V
–80V
GND
GND
+80V
+80V
CON2
+
SPKR
CON3
100nF
250VAC
X2
56Ω 1W
(4x 56Ω 1W
on underside)
L1
D7
UF4003
47Ω
470µF
100V
Q11
MJE15035
10nF
Q26
BC556
R1
4.7kΩ
R2
10kΩ
18kΩ
3.3kΩ
R1 = 35.7kΩ or 62kΩ || 82kΩ
R2 = 205Ω or 390Ω || 430Ω
REF2
TL431
220Ω
1µF
VR2
200Ω
NING!
GES PRESENT
100Ω 1W
100nF
470µF 100V
2.2kΩ
75pF
Q9
FZT458
Q8
BC639
68Ω
Q4
Q3
2x
BC546
D3
BAV21
22kΩ
1nF

Fig.6: all the parts for the amplifier module mount on this somewhat large PCB. As usual, take care with the orientations of the transistors, diodes, LEDs and electrolytic capacitors and don't get similar-looking parts mixed up. Note the two wire links required in the middle of the board. You should sleeve them with insulation just to be safe.

This overlay is shown split at actual size.

We can use E96 value resistors, with R1 = 35.7kΩ (+1%) and R2 = 205Ω(+0.1%). That is the easy method, and if you buy the set of hard-to-get parts from us, you'll get the 35.7kΩ and 205Ω resistors – see the note in the Parts List in *Part 1* last month.

A slightly more precise method for R1 and R2 is to use paralleled pairs of resistors, one fitted to the top side of the PCB as normal, and the other soldered across the pads underneath afterwards. These are 62kΩ || 82kΩ for R1 giving 35.3kΩ (–0.08%) and 390Ω || 430Ω giving 204.5Ω for R2 (+0.15%).

We don't think the +1% error using 35.7kΩ for R1 matters; the current-sensing 0.47Ω resistors have 5% tolerances, and the protection curves have a built-in safety margin. Still, if you're concerned about it, you can use the parallel pairs instead.

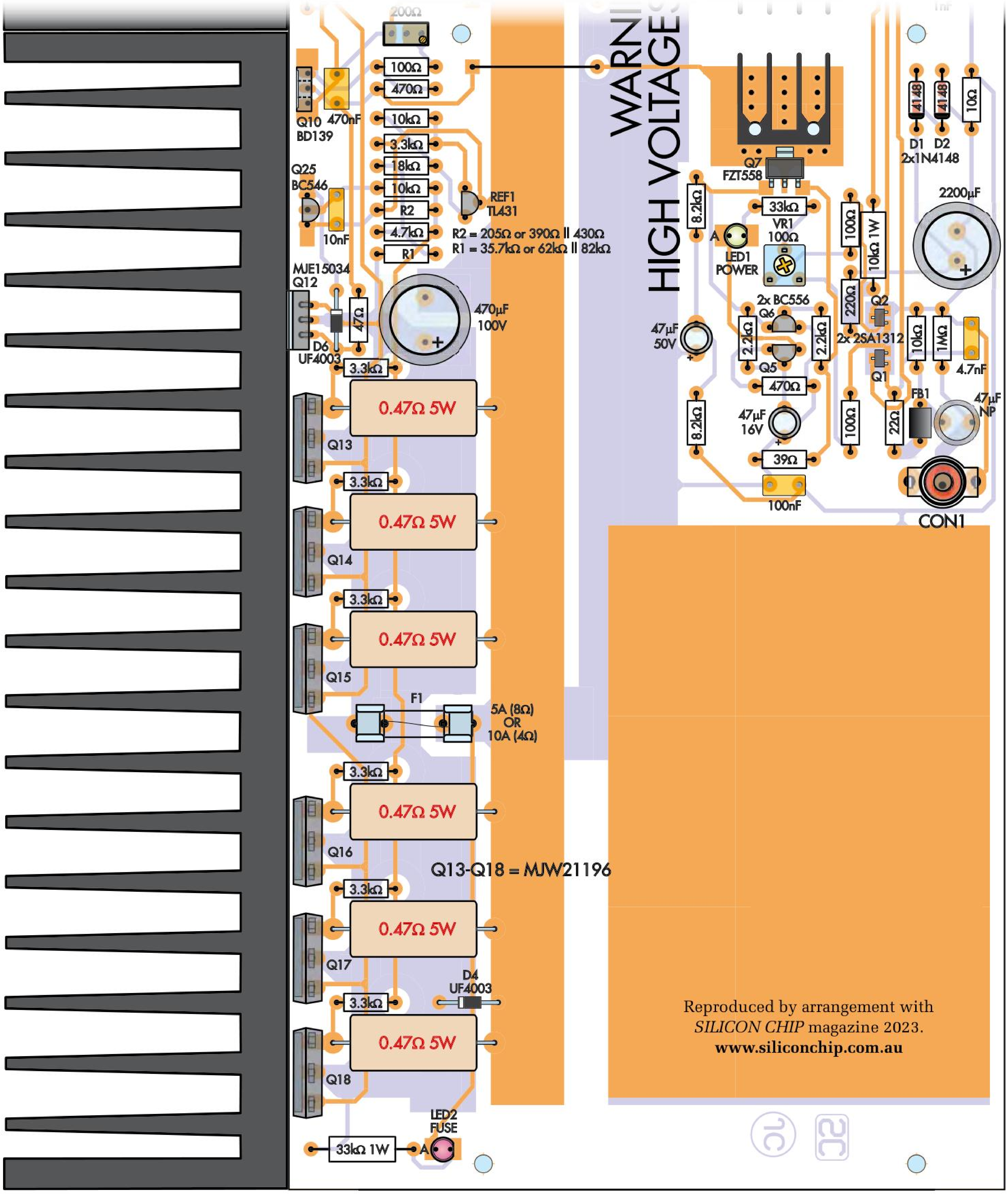
Fit these resistors in the eight positions, using your preferred method.

Now install the two small 1N4148 diodes (D1 and D2) with their striped ends (cathodes) as shown on the overlay diagram and PCB silkscreen. Next, fit the BAV21 diode (D3) with the cathode facing the same way.

The UF4003 diodes (D4-D7) can go in next. They are not all oriented the same way, so check Fig.6 and the PCB silkscreen.

There are two wire links in the middle of the PCB above Q7 and Q9. Make these using 0.7mm diameter tinned copper wire covered in 1mm heatshrink tubing over most of their lengths, leaving just the ends exposed.

Continue by mounting the 1W resistors, again being careful to check the values. For the 56Ω resistors near speaker connector CON3, four mount on the top side of the PCB and four on


200Ω
100Ω
470Ω
10kΩ
3.3kΩ
18kΩ
10kΩ
R2
4.7kΩ
R1
Q10
BD139
470nF
Q25
BC546
10nF
REF1
TL431
R2 = 205Ω or 390Ω || 430Ω
R1 = 35.7kΩ or 62kΩ || 82kΩ
MJE15034
Q12
47Ω
D6
UF4003
470μF
100V
WARNING
HIGH VOLTAGE
Q7
FZT558
8.2kΩ
33kΩ
VR1
100Ω
A
LED1
POWER
2x BC556
Q6
Q5
2.2kΩ
2.2kΩ
470Ω
47μF
50V
47μF
16V
8.2kΩ
39Ω
100nF
D1 D2
2x1N4148
4148
4148
10Ω
2200μF
100Ω
10kΩ 1W
220Ω
Q2
2x 2SA1312
Q1
10kΩ
1MΩ
4.7nF
100Ω
22Ω
FB1
47μF
NP
CON1
3.3kΩ
0.47Ω 5W
Q13
Q14
Q15
F1
5A (8Ω)
OR
10A (4Ω)
Q16
Q13-Q18 = MJW21196
Q17
D4
UF4003
Q18
LED2
FUSE
33kΩ 1W
A

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the underside. The PCB screen printing shows the resistor positions on both sides.

Next, you need to fit the small-signal transistors in TO-92 packages next. These are Q3 and Q4 (BC546) plus Q5 and Q6 (BC556). Leave Q25 and Q26 off at the moment, as these need to be mounted against the heatsink. However, you can fit the two TL431 references now, also in TO-92 packages (REF1 and REF2). Read the device markings carefully, and be sure to install the correct type at each location.

The three LEDs are mounted about 5mm off the PCB, taking care to orient them correctly and using the green LED for LED1. The longer lead is the anode, and this position is marked with an 'A' on the board.

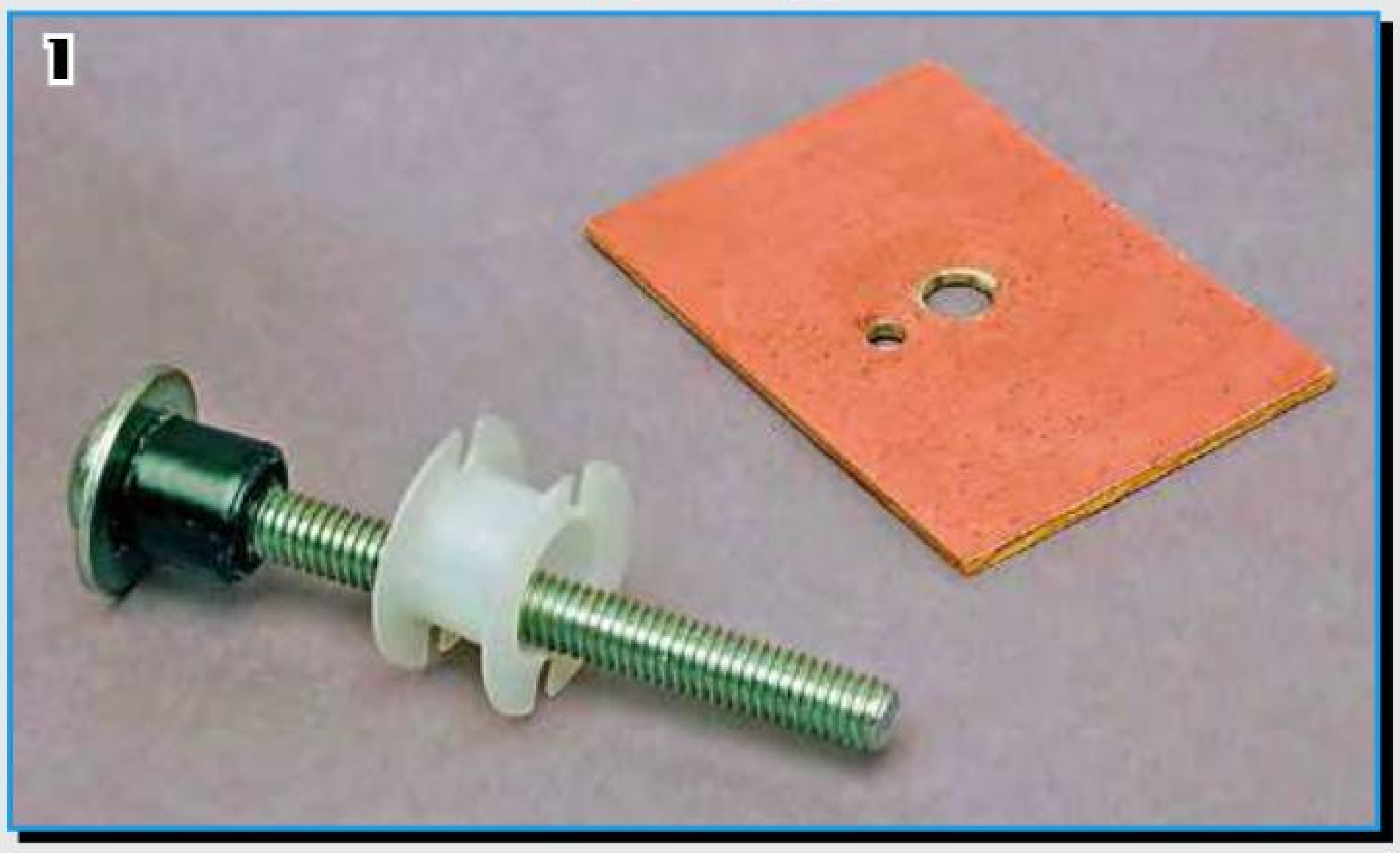
Fit the 75pF 200V capacitor now, along with the 1nF, 10nF, 100nF, 470nF and 1μF MKT capacitors. Follow with trimpot VR1, then VR2 with its adjustment screw towards the bottom of the board, as shown (right edge in Fig.6).

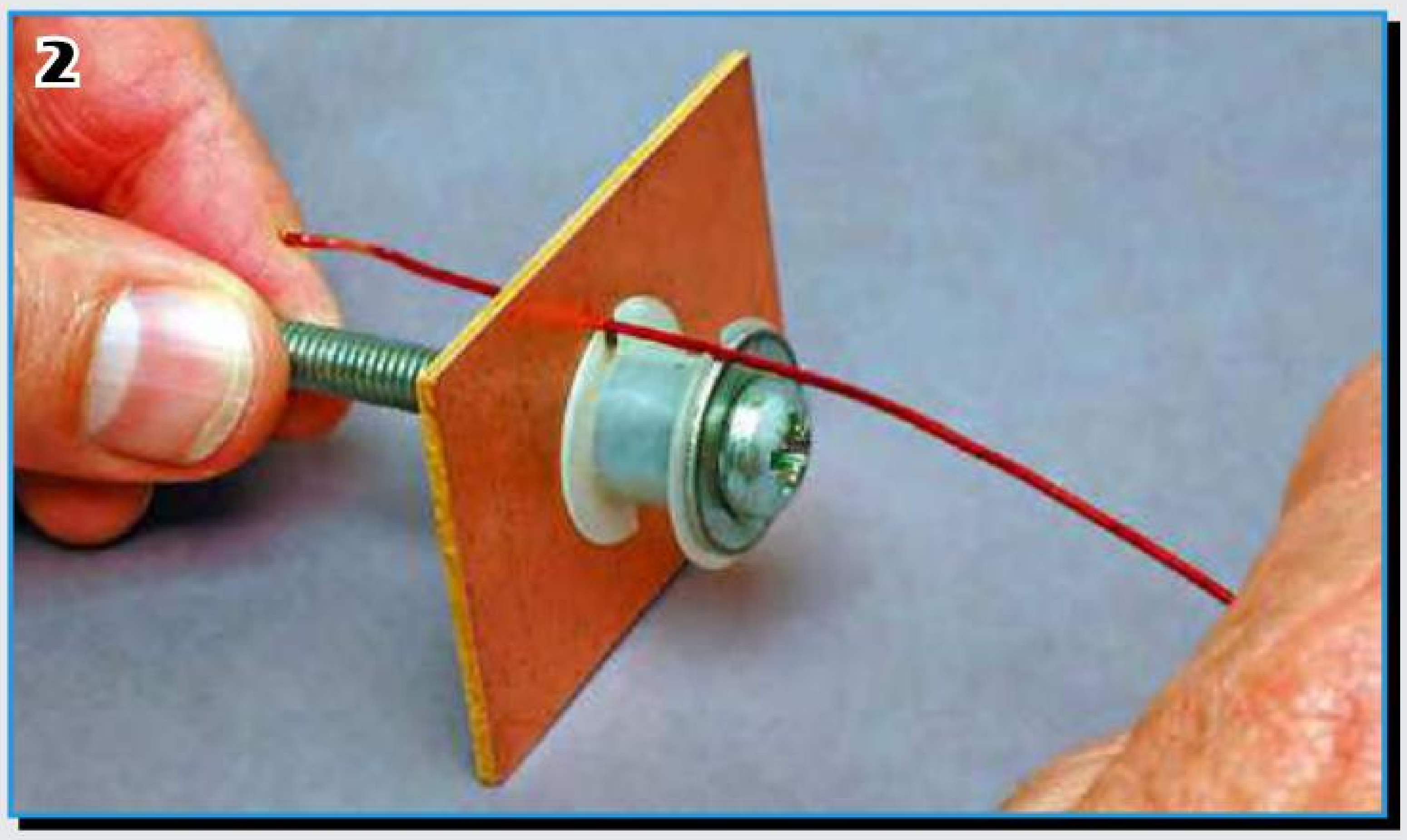
The four M205 fuse clips are next. Press them down fully onto the board before soldering and ensure that the retention clips are on the outside. The best approach to make sure the fuse clips are aligned correctly is to first fit a fuse to hold the fuse clips in position, then solder to the pads on the underside of the PCB.

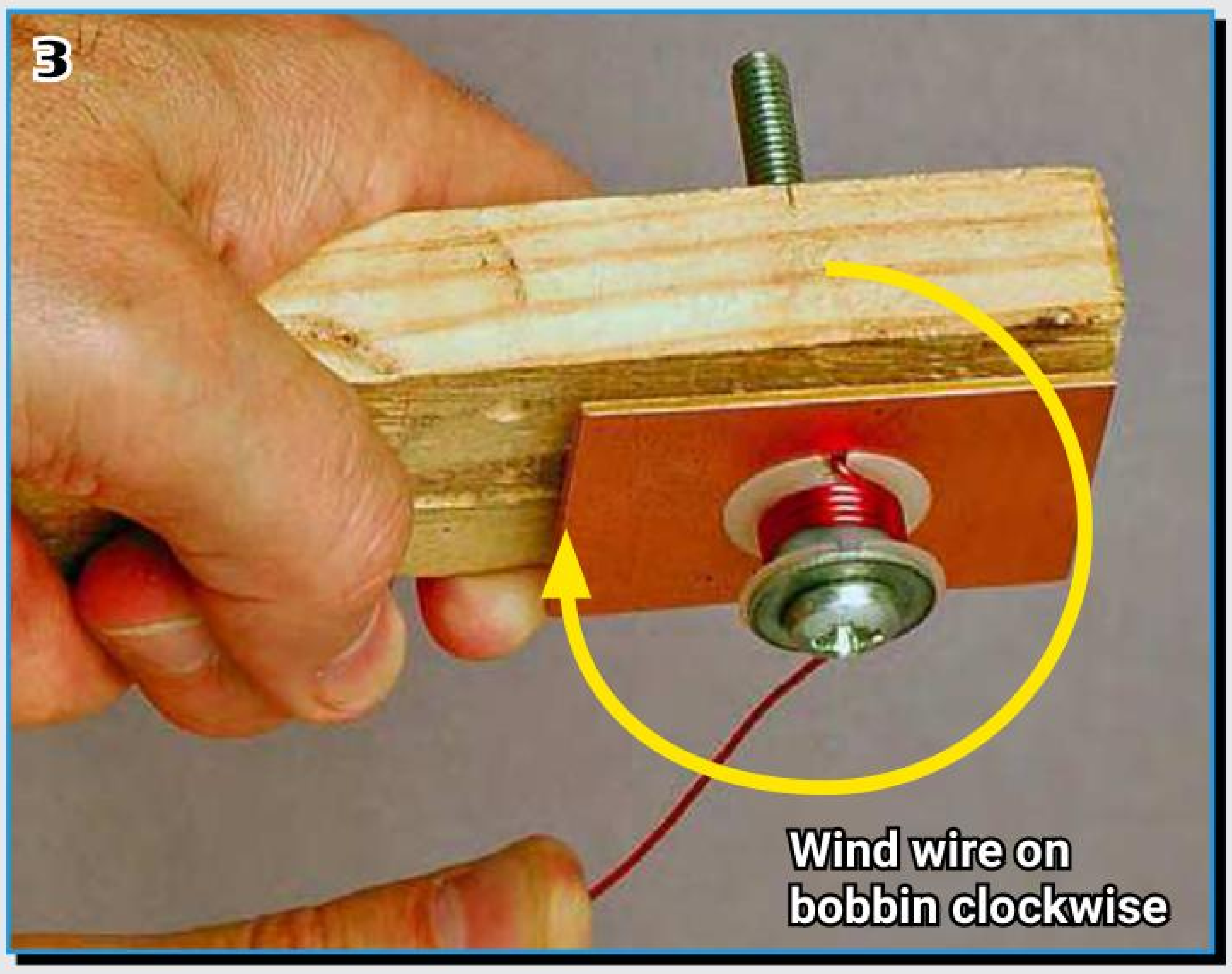
You can now solder in the 12 0.47Ω 5W resistors. These should be mounted about 2mm proud of the PCB so that cooling air can circulate beneath them. A cardboard spacer slid under the resistor bodies before soldering their leads can ensure consistent spacing.

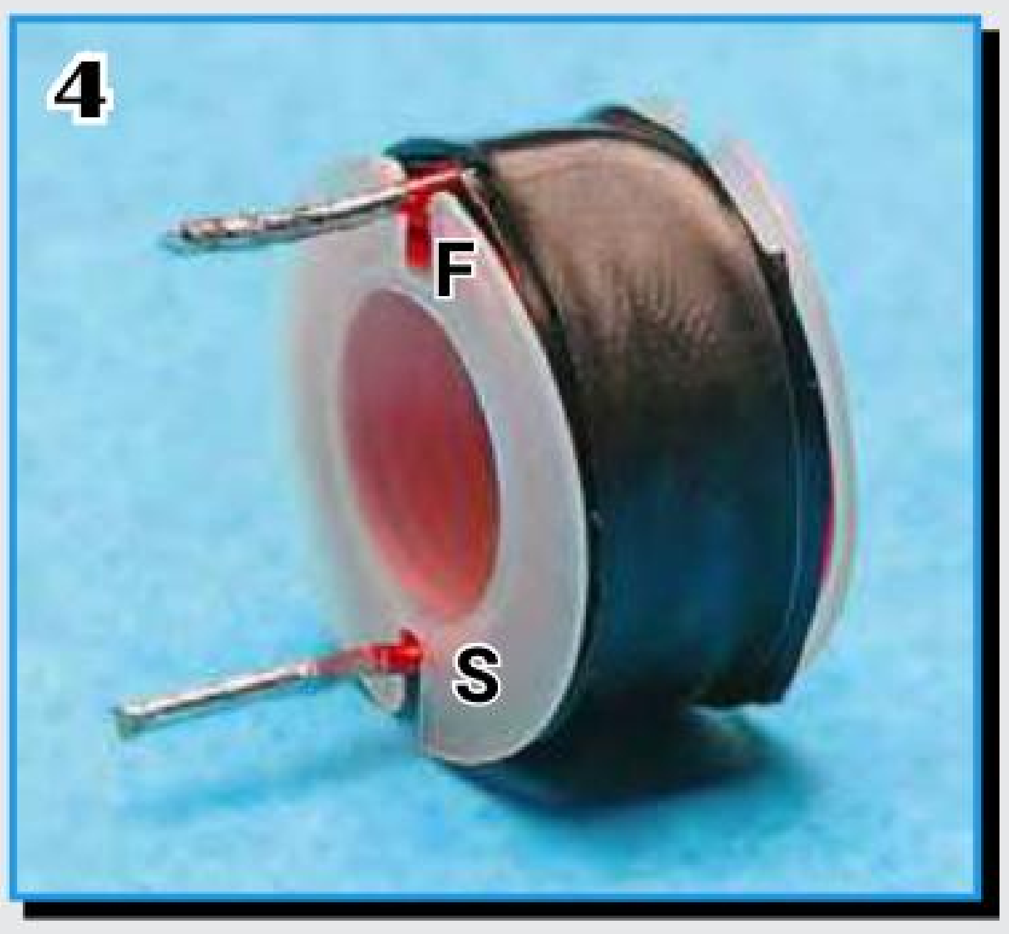
Now fit the connectors, ie, the RCA socket (CON1), the two-way socket for

L1 Winding Jig









These photos show how the winding jig is used to make the 2.2µH inductor. First, the bobbin is slipped over the collar on the bolt (1), then an end cheek is attached and the wire threaded through the exit slot (2). The handle is then attached and the coil tightly wound onto the bobbin using 13.5 turns of 1mm-diameter enamelled copper wire (3). The finished coil (4) is secured using a couple of layers of insulation tape and a band of heatshrink tubing.

The winding jig consists of a 70mm M5 bolt, two M5 nuts, an M5 flat washer, a piece of scrap PCB material or similar measuring approximately 40 x 50mm and a scrap piece of timber (about 140 x 45 x 20mm) for the handle.

In use, the flat washer goes against the bolt's head, after which a collar is fitted over the bolt to take the bobbin. This collar should be slightly smaller than the inner diameter of the bobbin and can be made by winding insulation tape onto the bolt, or from tubing. The collar needs to be of sufficient diameter for the bobbin to fit snugly without being too tight.

Drill a 5mm hole through the centre of the scrap PCB material, plus a 1.5mm exit hole about 8mm away that will align with one of the slots in the bobbin. The bobbin can be slipped over the collar, after which the scrap PCB end cheek is slipped over the bolt, ie, the bobbin is sandwiched into position between the washer and the scrap PCB.

Align the bobbin so that one of its slots lines up with the exit hole in the end cheek, then install the first nut and secure it tightly. Next, fit the handle by drilling a 5mm hole through one end, slipping it over the bolt and installing the second nut.

These photos show how the winding jig is used to make the 2.2µH inductor.

First, slip the bobbin over the collar on the bolt (1), then attach the end cheek and thread the wire through the exit slot (2). Next, attach the handle and wind the coil tightly onto the bobbin using 13.5 turns of 1mm-diameter enamelled copper wire (3). Finally, secure the finished coil (4) around the outside using 20mm diameter heatshrink tubing.

---

the loudspeaker connection (CON3) and the 6-way power connector (CON2). For CON3, first insert the terminal block plug into the socket and then install the socket into the PCB holes with the wire entries toward the outside edge of the PCB.

Now mount the 100nF X2 class capacitor located near CON3. The 47µF, 470µF and 2200µF electrolytic capacitors can then go in. The 47µF NP (non-polarised) electrolytic can go in either way around, but the others must all be oriented correctly.

Note that the 47µF capacitor above Q5 and Q6 must be rated to handle at least 50V (eg, a 63V type would be acceptable).

Mini heatsinks

Before fitting Q7 and Q9, you must first attach the heatsinks. Do this by inserting the mounting posts into the PCB holes and soldering these to the underside of the PCB. These will require a lot of heat from your soldering iron before the solder will successfully melt to secure the heatsink. Take care to avoid burning yourself on the hot heatsinks; wait until they are cool before mounting Q7 and Q9.

Now tackle Q7 (FZT558). It would help to spread a little flux paste on all four of its pads before placing the part. Align the device with the PCB pads and solder one of the pins to the PCB. Check for alignment and reheat the solder to realign if necessary. Then solder the remaining pins.

The metal tab needs to be soldered to the PCB right next to the heatsink. Again, you will need to heat it with your iron for an extended period due to the heatsink drawing heat away. Once the solder melts, though, solder the tab as quickly as possible to avoid overheating the device. Now install transistor Q9 (FZT458) in the same manner.

Winding inductor L1

The inductor (L1) is wound using a 0.9m length of 1mm diameter enamelled copper wire on a plastic bobbin (not 2m/1.25mm wire – an error in last month's Parts List). Use a winding jig as shown above. Without it, it's a much more difficult procedure, and you risk damaging the relatively fragile bobbin. Attach the bobbin to the jig, then wind 13.5 turns of 1mm diameter wire in the clockwise direction as shown, leaving about 20mm free at each end.

When finished, secure the winding with a narrow strip of insulation tape, then slip a 15mm length of 20mm diameter heatshrink tubing over the bobbin and heat it gently (be careful to avoid melting the bobbin). Next, use a small, sharp hobby knife to scrape away the enamel from the protruding lengths of wire around the whole circumference and tin the exposed copper at the ends, ensuring the solder sticks.

The inductor can then be installed on the PCB, oriented as shown. Secure it with a cable tie over the top of the winding and through to the underside of the PCB.

Preparing the main heatsink

The next step is to drill the heatsinks using the drilling templates provided (Fig.7). It is essential to place the holes accurately, so they are centred between the heatsink fins. That way, the screw heads will fit neatly between the fins.

Before drilling the heatsink, you will have to carefully mark out the hole locations using a very sharp pencil, then use a centre punch (or hammer and nail) to mark the hole centres. Next, drill 3mm holes at all the marked positions.

It is best to use a drill press as it's challenging to get the holes perfectly perpendicular to the mounting face otherwise. Use a small pilot drill to begin with (eg, 1.5mm), then step up the drill size to either 2.5mm or 3mm. Use a suitable lubricant when drilling the holes. Kerosene is the recommended lubricant for aluminium, but we found that light machine oil (eg, Singer or 3-in-1) also works well for jobs like this.

The holes have to go between the fins, so check that the hole positions are correct before drilling them.

Don't try drilling each hole in one pass. When drilling aluminium, it's important to regularly remove the bit from the hole and clear away the metal swarf. If you don't do this, the aluminium swarf has a nasty habit of jamming the drill bit and breaking; it and can also scratch the heatsink face. Relubricate the hole and the bit each time before you resume drilling.

At this stage, 2.5mm holes can be drilled in the bottom edge of the heatsink, ready to be tapped with an M3 thread. Do this at two places along the bottom edge on each heatsink. This is for mounting the heatsinks to the chassis later.

Tapping

To tap the underside mounting holes, you will need an M3 intermediate (or starting) tap (not a finishing tap). The trick here is to take it nice and slowly. Keep the lubricant up and regularly wind the tap out to clear the metal swarf from the hole. Relubricate the tap each time before resuming.

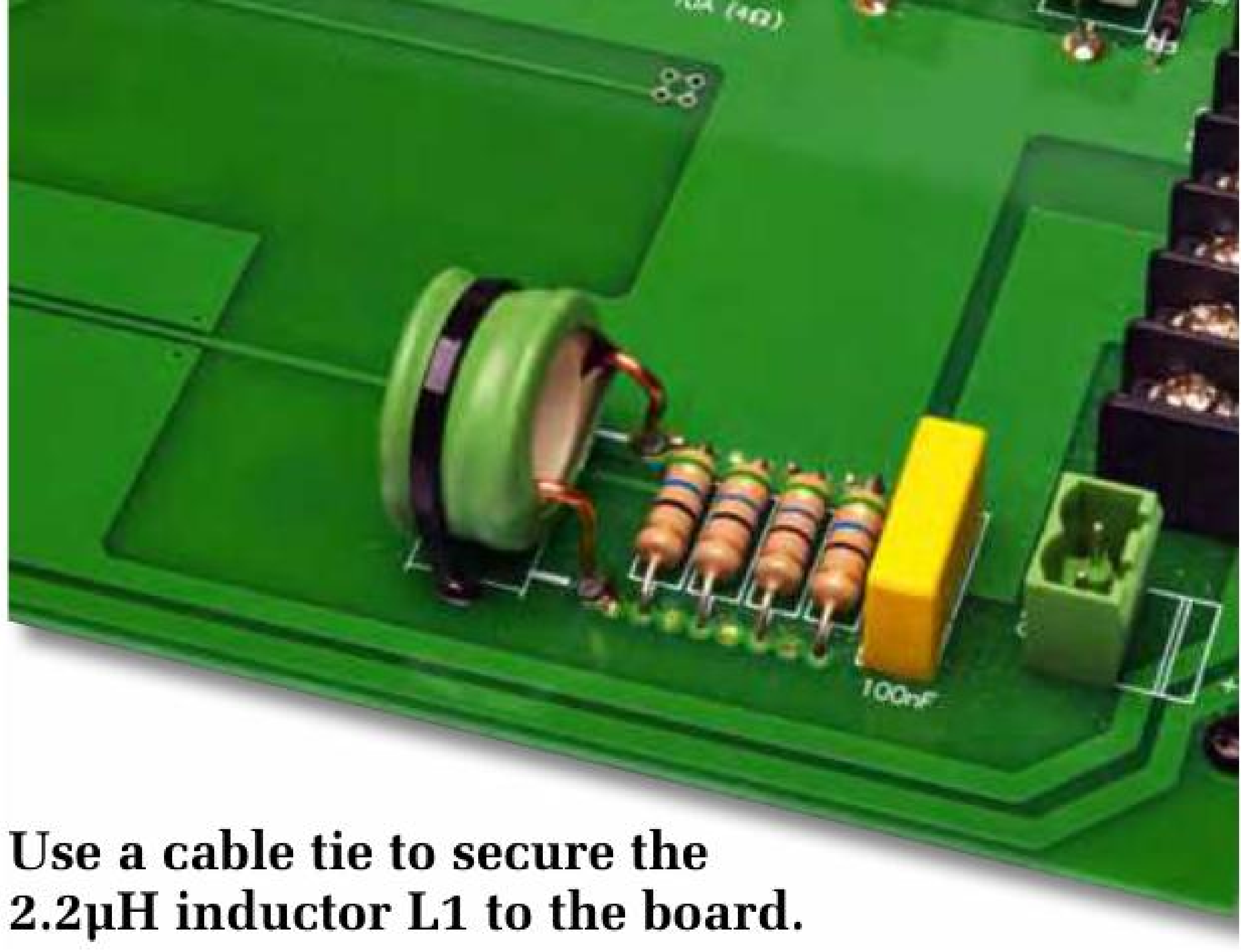
Do not apply undue force to the tap. It's all too easy to break a tap in half if you are heavy-handed. Similarly, if you encounter any resistance when undoing the tap from the heatsink, gently rotate it back and forth and let it cut its way back out. In short, don't force it, or it will break.

Finally, lightly deburr hole edges using an oversized drill bit and clean off any aluminium particles or swarf. Check that the area around the holes is perfectly smooth, or the insulating washers could be damaged. Scrub the heatsink thoroughly using water and detergent and allow it to dry.

Final assembly

Fig.8 shows the transistor mounting details. Start by mounting transistors Q13 to Q24, noting that Q13-Q18 are the MJW21196 transistors while Q19-Q24 are the MJW21195 transistors. Q13-Q18 are mounted on the left-hand heatsink and Q19-24 on the right-hand heatsink. The locations for these are shown in Fig.7 (you can also refer to Fig.6).

These all mount with a silicone insulating washer between each transistor and the heatsink face. They are secured using M3 x 20mm machine screws inserted between the heatsink fins and a flat metal washer and M3 nut against the transistor face. Do *not* tighten the screws yet, so you can move the insulation washers and transistors to allow mounting onto the PCB.



Use a cable tie to secure the 2.2µH inductor L1 to the board.

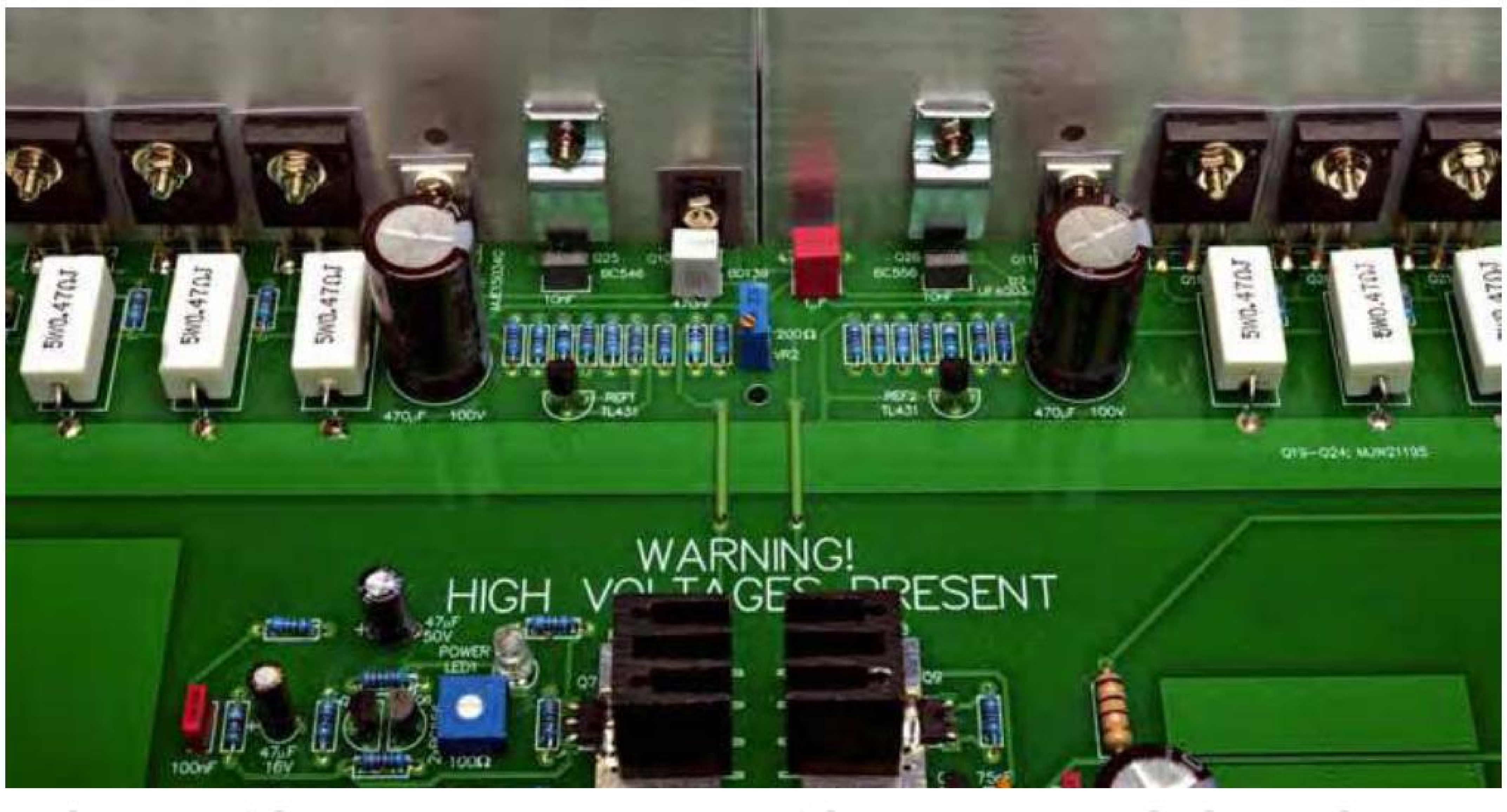
Q12 (the MJE15034) on the left-hand heatsink and Q11 (the MJE15035) on the right-hand heatsink need silicone TO-220 insulating washers and an insulating bush inserted into the device's tab hole before being secured with an M3 x 15mm screw and M3 nut. Also leave these loose for the moment.

Q10, the BD139, mounts with the metal face toward the heatsink and a TO-220 silicone washer between the heatsink and transistor. Attach it with an M3 x 15mm screw and M3 nut, and again, leave the screw connection loose.

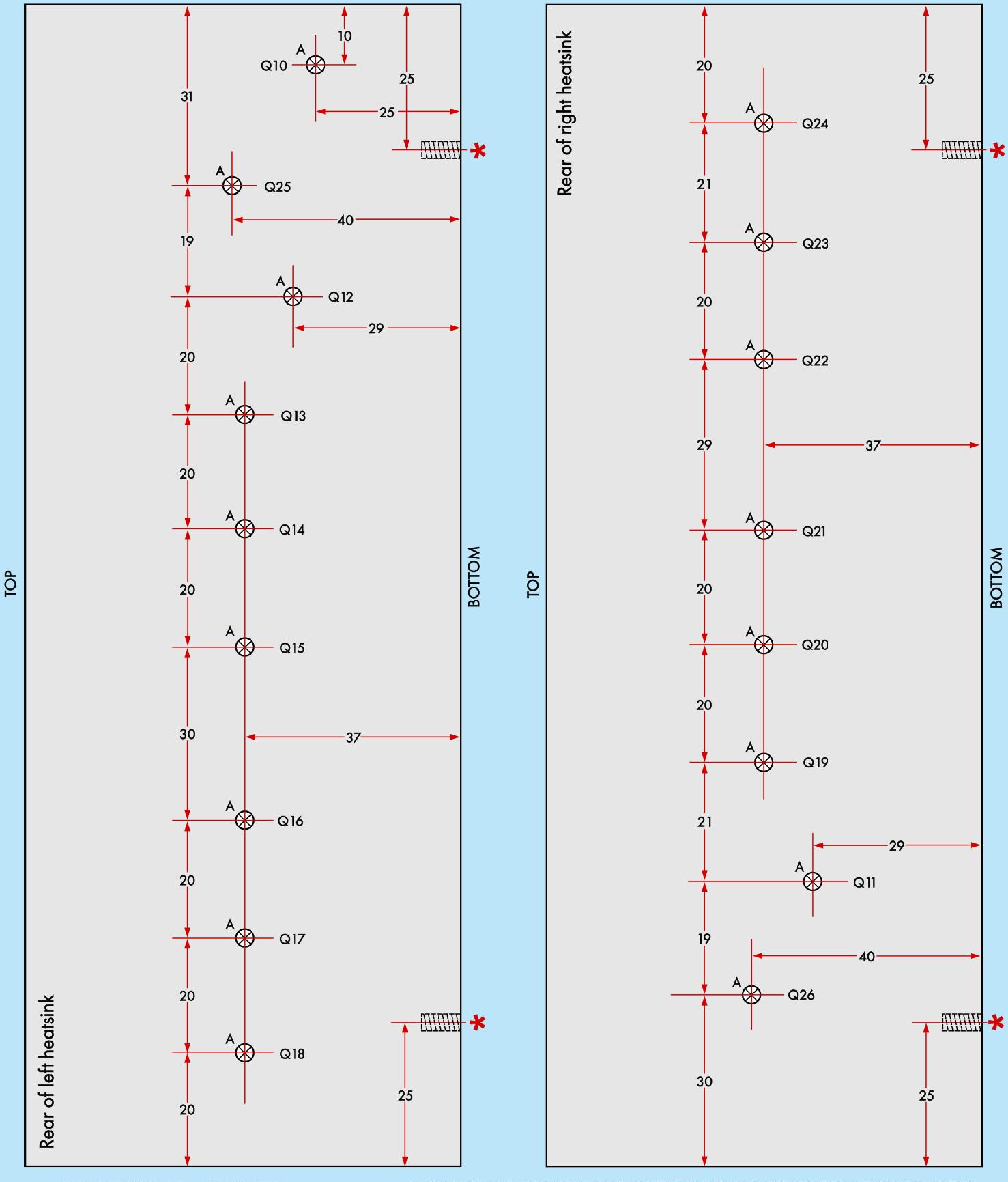
Now mount the PCB on six M3-tapped 9mm spacers and sit it on a flat surface. Lower each heatsink, one at a time, inserting the transistor leads through the appropriate holes. Once they're in, push the board down so that all four spacers (and the heatsink) are in contact with the benchtop.

This adjusts the transistor lead lengths and ensures that the bottom of the board sits exactly 9mm above the bottom edge of the heatsink.

Check that the correct transistor is in each position and adjust the PCB assembly horizontally so that each extends an equal 1mm beyond the side of the heatsink. Now tighten all the transistor screws just enough that they are held in place while keeping the insulating washers correctly aligned. The rear of each heatsink should be flat against the transistor mounting edge of the PCB.



A close-up of the mounting arrangement of the transistors to the heatsink.


TOP
BOTTOM
Rear of left heatsink
A
Q10
10
25
25
31
*
Q25
40
19
Q12
29
20
Q13
20
Q14
20
Q15
30
37
Q16
20
Q17
20
Q18
20
25
Rear of right heatsink
20
25
Q24
21
Q23
20
Q22
29
37
Q21
20
Q20
20
Q19
21
29
Q11
19
40
Q26
30
25

ALL HOLES ‘A’ ARE 3mm IN DIAMETER

* DRILL & TAP FOR M3 THREAD IN UNDERSIDE EDGE OF HEATSINK BASEPLATE (2 PER HEATSINK)

ALL DIMENSIONS IN MILLIMETRES

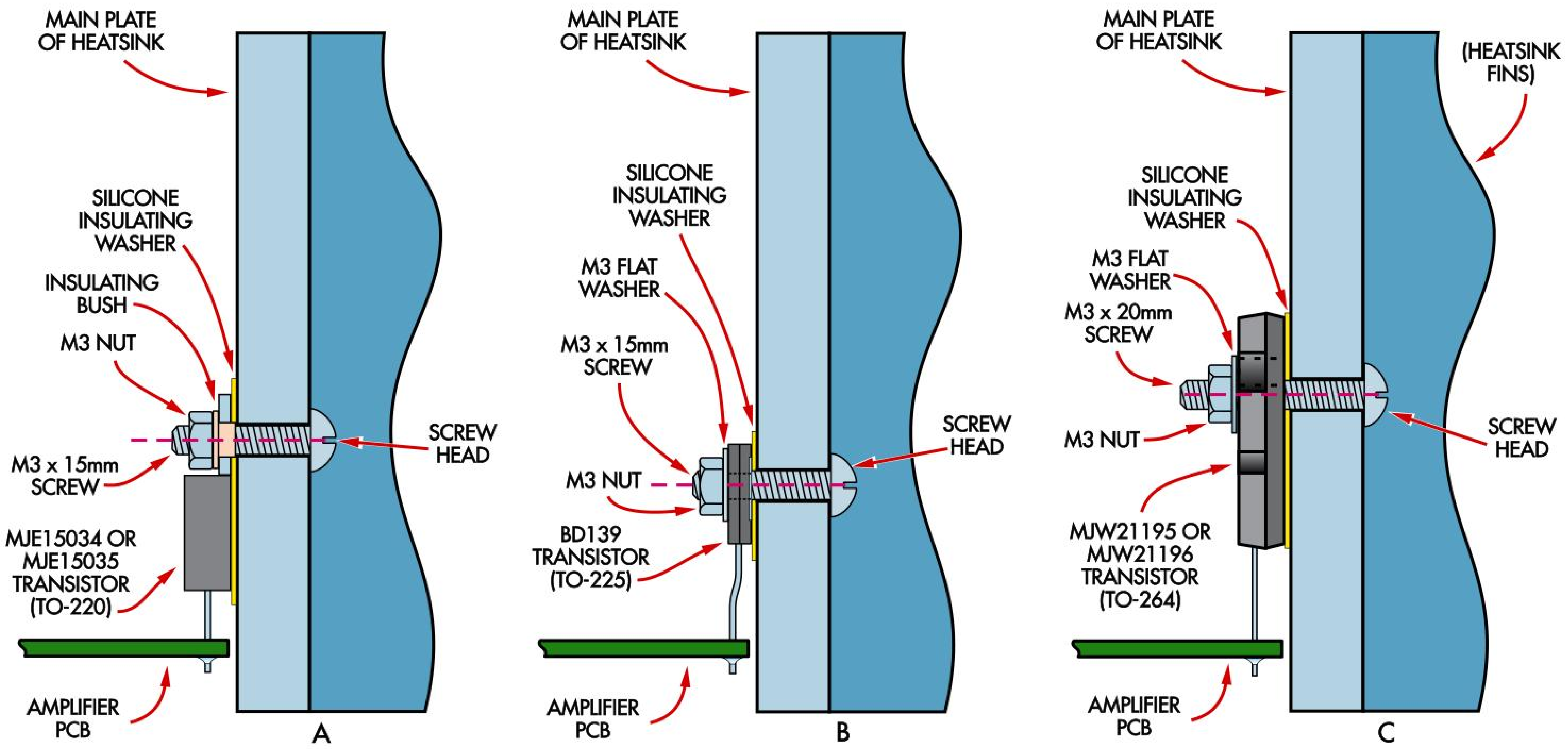
Fig.7: drill the two side-by-side heatsinks as shown here. You can drill the transistor mounting holes through the heatsink using a 3mm bit and then mount the transistors using screws, nuts and washers. The underside edge is drilled to 2.5mm and tapped for M3 in two places on each heatsink so that it can be mounted to the chassis.

The next step is to lightly solder the transistor leads from the top of the PCB, or at least as many leads as you can easily access from the top. Then carefully turn the whole assembly upside down and prop the front edge of the board up by placing books or something similar under the board so that the PCB is maintained at right angles to the heatsink.

If you don’t have anything handy that you can stack to a suitable height, you can cut a couple of cardboard cylinders to 63mm (eg, from discarded paper towel rolls) to use as temporary supports.

If you don’t do this, it will sag under its own weight and remain in this condition after the leads are soldered.

Now you can solder the remaining transistor leads and add extra solder to any that need it. Make sure the joints are good since they can carry many amps at full power. When finished,


MAIN PLATE OF HEATSINK
SILICONE INSULATING WASHER
INSULATING BUSH
M3 NUT
M3 x 15mm SCREW
MJE15034 OR MJE15035 TRANSISTOR (TO-220)
AMPLIFIER PCB
SCREW HEAD
A
MAIN PLATE OF HEATSINK
SILICONE INSULATING WASHER
M3 FLAT WASHER
M3 x 15mm SCREW
M3 NUT
BD139 TRANSISTOR (TO-225)
AMPLIFIER PCB
SCREW HEAD
B
MAIN PLATE OF HEATSINK
(HEATSINK FINS)
SILICONE INSULATING WASHER
M3 FLAT WASHER
M3 x 20mm SCREW
M3 NUT
MJW21195 OR MJW21196 TRANSISTOR (TO-264)
AMPLIFIER PCB
SCREW HEAD
C

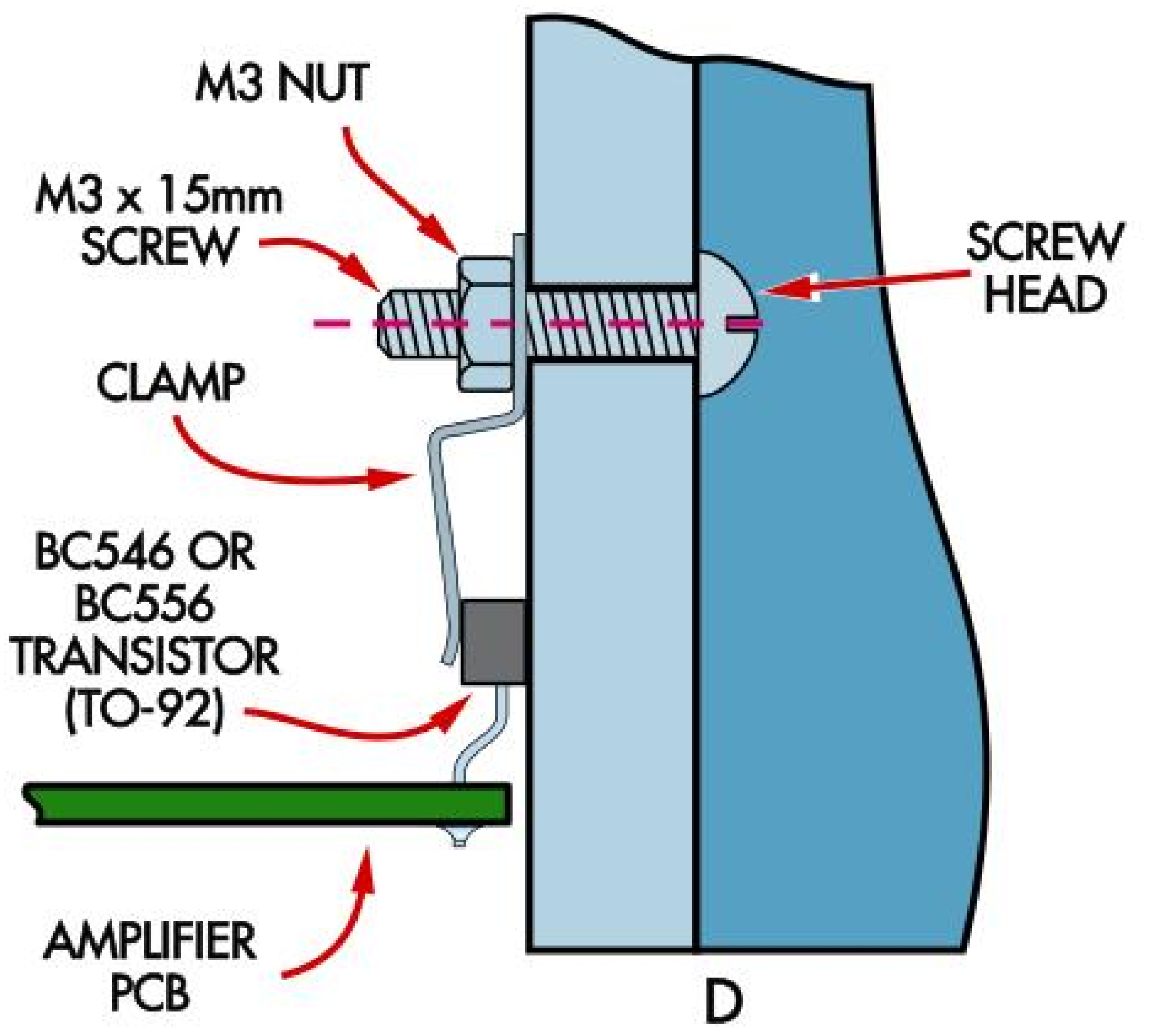

M3 NUT
M3 x 15mm SCREW
SCREW HEAD
CLAMP
BC546 OR BC556 TRANSISTOR (TO-92)
AMPLIFIER PCB
D

Fig.8: use this diagram as a guide for mounting the various devices to the heatsink. Note the use of silicone insulating washers for all the large devices (no need for Mica given how spread out the heat load is) and the plastic bushes for the TO-220 devices with fully exposed metal tabs.

trim the leads and turn the board right-way-up again.

Next, tighten the transistor mounting screws to ensure good thermal coupling between the devices and the heatsink. They need to be tight, but don't get out your breaker bar or impact driver.

Checking device isolation

Now check that the transistors are all electrically isolated from the heatsink. Do this by switching your multimeter to a high-ohms range and measuring the resistance between the heatsink mounting surface and the collectors of the heatsink-mounted transistors.

For transistors Q13-Q24, it's simply a matter of checking between each of the fuse clips closest to the heatsink and the heatsink itself on each side of the *Amplifier*. That's because the device collectors in each half of the output stage are connected together and run to their respective fuses. You should get a reading above 10MΩ, and quite likely 'OL' because it should be too high for your DMM to read.

Testing shorts for transistors Q10 (the V_{BE} multiplier), Q11 and Q12 is different. In this case, you have to check for shorts between the centre (collector) lead of each device and the heatsink.

If you do find a short, undo each transistor mounting screw in turn until the short disappears. It's then simply a matter of locating the cause of the problem and remounting the offending transistor. Be sure to replace the insulating washer if it has been damaged in any way (eg, punched through).

Q25 (BC546) and Q26 (BC556) can be mounted now. These are held in position using transistor clamps attached to the heatsink by 15mm M3 screws and nuts.

Apply a smear of heatsink compound to the flat face of each, mount the transistor clamps and position each transistor so the clamps will hold them in place at approximately the centre of the transistor body. Then tighten the screws. Turn the PCB assembly upside-down and solder and trim the transistor leads.

Now you must remove the three support spacers from the edge of the board adjacent to the heatsink. This edge of the board must be supported only by the heatsink transistor leads. This avoids the risk of eventually

When finished, our 500W Amplifier will have fans attached at the back of the heatsink via a metal bracket on the base of the case.

cracking the PCB tracks and pads around the heatsink-mounted transistors due to thermal expansion and contraction as the assembly heats up and cool down.

Coming up next

That completes the assembly of the *Amplifier Module*. Next month, we will describe the power supply, how to power up and test the *Amplifier* and give full details on building the *Amplifier* into a vented aluminium metal case (shown on the previous page with its lid removed) and keeping it cool, even under full load conditions.

Parts List – Complete 500W Amplifier

1 assembled 500W Amplifier Module (as described in *PE*, April and May 2023)
1 assembled Amplifier Clipping Indicator set up for ±80V DC supplies (see *PE*, April 2023)
1 assembled Fan Controller and Loudspeaker Protector with three 120mm PWM fans (see *PE*, February 2023)
1 12V 15W switch-mode mains supply **[Jaycar MP3296, Altronics M8728]**

Chassis

1 3U Aluminium rack enclosure, 558.80mm x 431.80mm x 133.35mm, made from:
1 Bud Industries RM-14222 Rackmount Chassis Kit (front, back and sides) **[Digi-Key 377-1392-ND]**
1 Bud Industries TBC-14253 Solid Rackmount Cover (for base) **[Digi-Key 377-1396-ND]**
1 Bud Industries TBC-14263 Perforated Rackmount Cover (for lid) **[Digi-Key 377-1397-ND]**
4 equipment mounting feet **[Jaycar HP0830/HP0832, Altronics H0890]**
1 400mm length of 20 x 20mm x 3mm aluminium angle **[hardware store]**
1 220 x 60mm front panel label

Power Supply

1 800VA toroidal mains transformer with 2 x 115V AC and 2 x 55V AC windings **[RS Components 1234050]**
1 toroidal transformer mounting disc (drill hole out to 8mm diameter) **[RS Components 6719202]**
2 Neoprene washers for toroidal transformer **[RS Components 6719218]**
1 35A 400V bridge rectifier (BR1) **[MB354, KPC3504 or similar]**
1 208 x 225 x 0.8mm insulating sheet (Prespahn, Elephantide or similar) **[Jaycar HG9985]**
1 295 x 125 x 3mm plastic sheet (Perspex, Polycarbonate, PVC, acrylic or similar)
1 IEC mains input connector with fuse **[Jaycar PP4004, Altronics P8324]**
1 IEC mains connector insulating boot **[Jaycar PM4015]**
1 IEC mains power cord
1 M205 3.15A slow-blow fuse (F3)
1 DPDT mains switch with red neon lamp (S1) **[Jaycar SK0982, Altronics S3242B]**
1 3-way 6A mains-rated terminal strip **[Jaycar HM3194, Altronics P2130A]**
8 10,000µF 100V electrolytic capacitors **[Jaycar RU6712 with mounting brackets]**
6 15kΩ 1W resistors
2 5mm LEDs (LED4, LED5)
6 5mm yellow insulated crimp eyelets **[Jaycar PT4714, Altronics H2061B]**
6 6.3mm blue insulated female spade crimp connectors **[Jaycar PT4625, H1996B]**
10 150mm cable ties
7 adhesive panel mount cable anchors
assortment of heatshrink tubing

Wire and cable

300mm of 7.5A or 10A Earth wire (green/yellow striped) [can be stripped from three-core mains flex]
1 1.5m length of twin-core 7.5A sheathed mains cable
5m of 0.5mm diameter copper wire (eg, copper picture frame wire)
400mm of dual-core shielded microphone cable (or single-core if RCA input socket is used)
2m of red 25A-rated hookup wire, 2.9mm^2 **[Jaycar WH3080]**
2m of black 25A-rated hookup wire, 2.9mm^2 **[Jaycar WH3082]**
1m of figure-8 wire, 2.93mm^2 per conductor **[Jaycar WB1732]**
1m of figure-8 wire, 2.5mm^2 per conductor **[Jaycar WB1712]**
2m of figure-8 wire, 0.76mm^2 per conductor **[Jaycar WB1708]**
1m of figure-8 wire, 0.44mm^2 per conductor **[Jaycar WB1704]**

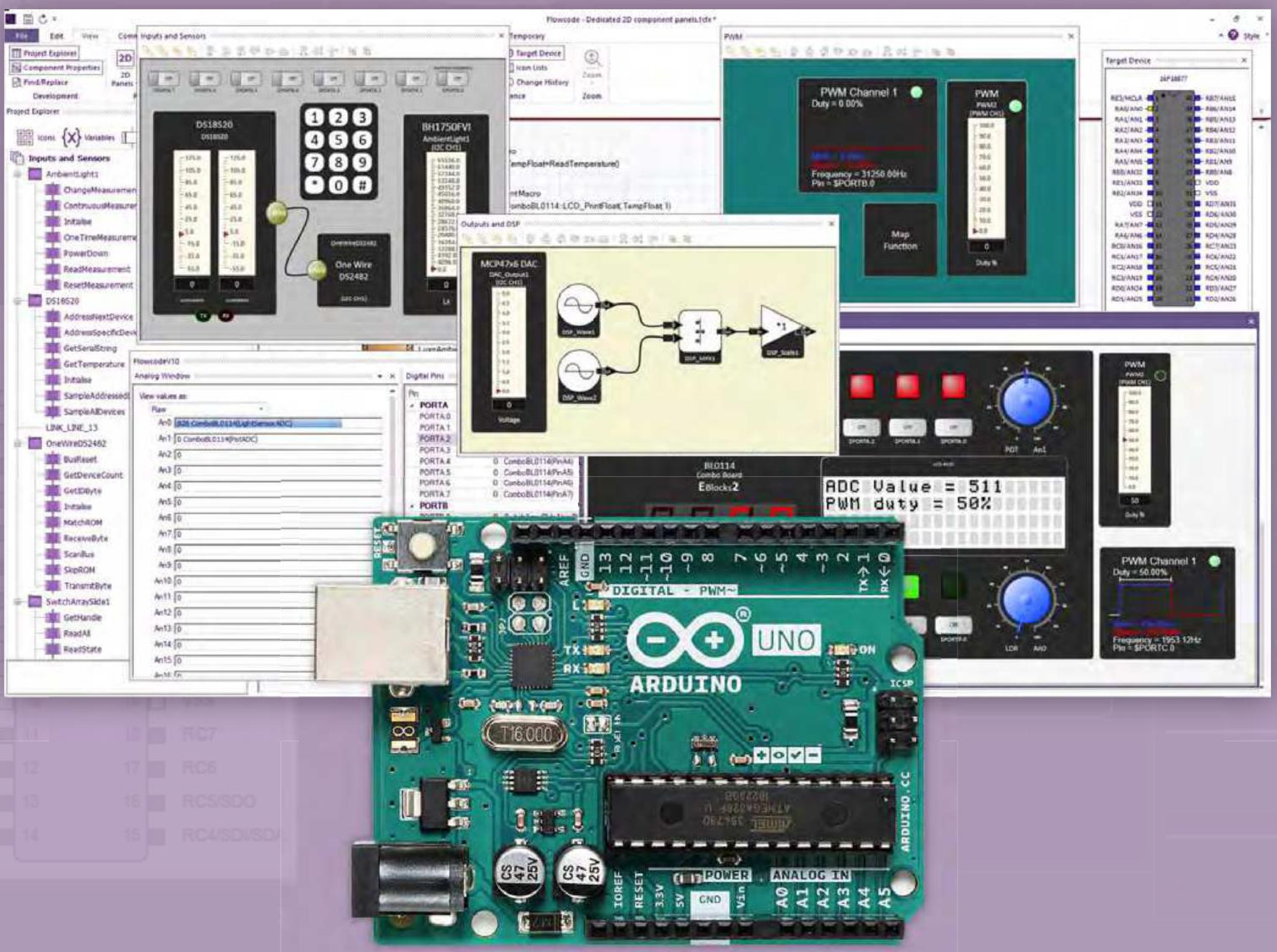
Hardware, including screws

2 No.4 x 6mm self-tapping screws (or two M2 x 6mm machine screws and two M2 nuts)
1 M8 x 75mm bolt, M8 hex nut and washer for transformer [hardware store]
8 M4 x 50mm machine screws
1 M4 x 20mm machine screw
3 M4 x 15mm machine screws
22 M4 x 10mm machine screws
4 M4-tapped joiners
39 M4 hex nuts
3 M4 star washers
2 M3 x 15mm machine screws
4 M3 x 12mm countersunk head machine screws
10 M3 x 10mm machine screws
11 M3 x 9mm Nylon standoffs
2 M3 x 6mm machine screws
22 M3 x 5mm machine screws
12 M3 hex nuts

Other parts

1 SPDT 30A relay, 12V coil (RLY1) **[Altronics S4211]**
3-pin female XLR panel connector **[Jaycar PS1054, Altronics P0903]** (or insulated panel-mount RCA socket)
1 panel-mount pair of heavy-duty loudspeaker terminals **[Jaycar PT0457, Altronics P9257A]**
1 RCA line plug
1 panel-mount bezel for 5mm LED **[Jaycar SL2610, Altronics Z0220]**
3 6.3mm yellow insulated female spade crimp connectors **[Jaycar PT4725, Altronics H1842A]**
1 560nF 100V MKT capacitor
2 10kΩ lug-mount NTC thermistors **[Altronics R4112]**

Here is the complete parts list for the 500W Amplifier needed for the final constructional article next month.
As always, use the above references to determine part specifications if the above suppliers are not local to you and you need to purchase from more convenient or cheaper alternative sources.


ADC Value = 511
PWM duty = 50%
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- low RF leakage

FREQ
FREQ STEP
MHz kHz Hz
FM DEV
CTION
ICY
AD9851 DDS SIGNAL GENERATOR
ON
AM
CW
FM

Precision AM-FM DDS Signal Generator

This *Signal Generator* aims to provide very high calibrated accuracy with an error of just ten parts in a billion (1 in 10^8), which translates to 0.1Hz at 10MHz. It also has plenty of features, including amplitude and frequency modulation.

Numerous cheap signal generators are available online, but their accuracy leaves a lot to be desired. So I decided that if I wanted to have a maximum error of 0.1Hz at 10MHz, which would be ideal, I would have to design one.

The first decision I had to make was what I wanted it to look like. This would determine the type of enclosure needed, the display and the controls. With the current worldwide shortage of many components, choosing these parts can be difficult. There is no escaping the fact that most advanced components are only available in surface-mount packages, some with very small lead pitch.

Good shielding is essential for a signal generator. You want the signal to be via the output connector and not radiated from the device itself. For this reason, I chose a diecast aluminium box with a minimum number of apertures that need to be cut. The largest of these is for the display, and by using a small OLED module, RF leakage is cut down substantially.

Next, I had to decide whether to use ready-made modules or individual parts. Let's take the frequency generating chip, the Analog Devices AD9851. This is available on a prebuilt module with its own clock generator and output filtering.

Those have several problems, starting with the crystal oscillator module, which is just a standard cheap 30MHz unit. The accuracy and temperature stability is dubious and does not fit my design criteria.

Yes, you can remove it and add a wire link to an accurate temperature-compensated crystal oscillator (TCXO) on the main board, but it's not ideal. Applying amplitude modulation requires access to the RSET pin on the AD9851 chip, meaning another wire link to the main board.

The type of output I want to use requires a wideband transformer from two pins on the DDS chip. This is now getting into the 'too hard' category and is the final reason for rejecting the prebuilt module.

The cheapest Arduino modules mostly use an ATMega328 chip running at 16MHz. All the I/O pins are brought out, so there are no changes needed. But with my design, the number of pins available from the ATmega328 are inadequate, so a fancy pin-sharing arrangement would be necessary.

Also, much processing is needed to apply frequency modulation, and the 16MHz clock speed is marginal for this. So instead, I am using a 44-pin ATmega644. This gives me more than enough I/O pins and I can arrange for it to run at 20MHz for a 25% boost in processing power.

The display needs to convey lots of information, but a large screen is ruled out by the need for a small cutout to give low RF leakage. That's why I chose a 0.96-inch (24mm) diagonal OLED. It does have rather small characters, but conveys all the needed information.

By eliminating ready-made modules, the final PCB size (and thus the enclosure) is much smaller. Diecast boxes are expensive, so using a smaller one does make it considerably cheaper.

The final major component needed is another DDS chip, the AD9833. This only comes in a tiny 10-pin MSOP package but it is available on a small, ready-made module. I was tempted to use such a module in my design, and could have fitted it in, but I did not want yet another oscillator running in the unit (the module has an onboard 25MHz oscillator).

So I am just using the bare, standalone chip. It gets its 20MHz clock source from the clock output pin on the ATmega644 processor.

Component Selection

Given the present severe shortage of electronic components, I paid particular attention to being able to source parts from several suppliers. The AD9851 DDS chip is available from several suppliers on AliExpress for about £10-12

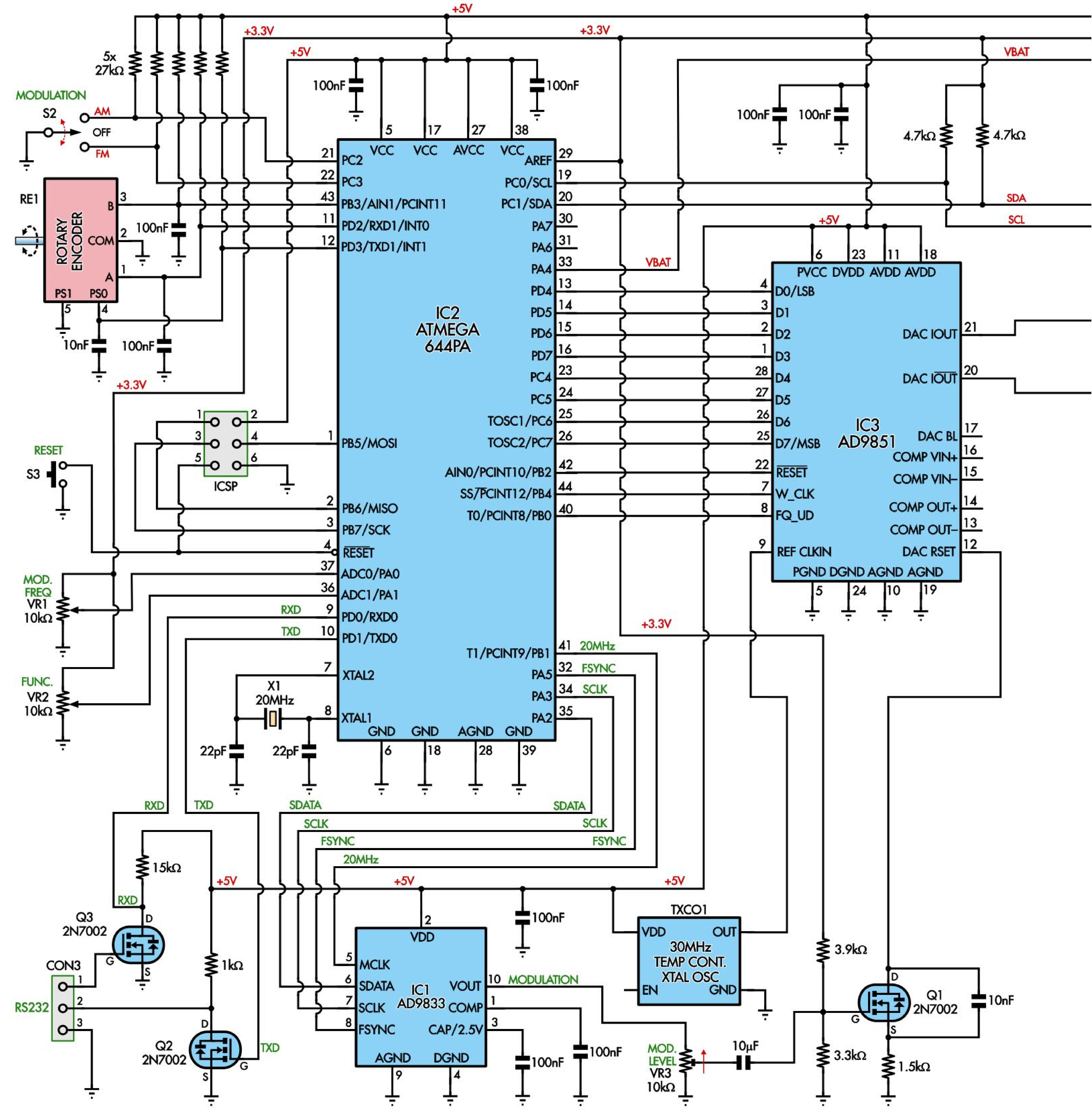

+5V
+3.3V
VBAT
SDA
SCL
5x 27kΩ
MODULATION
S2
AM
OFF
FM
RE1
ROTARY ENCODER
B
COM
A
PS1
PS0
100nF
10nF
4.7kΩ
IC2
ATMEGA 644PA
VCC
AVCC
AREF
PC2
PC3
PB3/AIN1/PCINT11
PD2/RXD1/INT0
PD3/TXD1/INT1
PC0/SCL
PC1/SDA
PA7
PA6
PA4
PD4
PD5
PD6
PD7
PC4
PC5
TOSC1/PC6
TOSC2/PC7
AIN0/PCINT10/PB2
SS/PCINT12/PB4
T0/PCINT8/PB0
PB5/MOSI
PB6/MISO
PB7/SCK
RESET
ADC0/PA0
ADC1/PA1
PD0/RXD0
PD1/TXD0
XTAL2
XTAL1
T1/PCINT9/PB1
PA5
PA3
PA2
GND
AGND
ICSP
RESET
S3
MOD. FREQ
VR1 10kΩ
FUNC.
VR2 10kΩ
RXD
TXD
X1 20MHz
22pF
20MHz
FSYNC
SCLK
SDATA
IC3
AD9851
PVCC DVDD AVDD AVDD
D0/LSB
D1
D2
D3
D4
D5
D6
D7/MSB
RESET
W_CLK
FQ_UD
REF CLKIN
DAC IOUT
DAC IOUT
DAC BL
COMP VIN+
COMP VIN–
COMP OUT+
COMP OUT–
DAC RSET
PGND DGND AGND AGND
15kΩ
Q3 2N7002
CON3
RS232
1kΩ
Q2 2N7002
IC1 AD9833
VDD
MCLK
SDATA
SCLK
FSYNC
VOUT
COMP
CAP/2.5V
AGND
DGND
MODULATION
TXCO1
VDD
OUT
30MHz TEMP CONT. XTAL OSC
EN
GND
MOD. LEVEL
VR3 10kΩ
10µF
3.9kΩ
3.3kΩ
Q1 2N7002
1.5kΩ

Fig.1: the Signal Generator circuit is based on three main chips: IC1, the AD9833 DDS that's used for the AM signal; IC2, the ATmega644 microcontroller; and IC3, the AD9851 DDS that produces the output signal. IC3 is clocked by the high-precision 30MHz TCXO, while IC1 and IC2 are both clocked by the same 20MHz crystal (X1) driven by IC2's internal amplifier. Microcontroller IC2 also monitors user controls EN1, VR1 and VR2.

delivered. The AD9833 DDS chip is also available for about £2 plus delivery from numerous AliExpress sellers.

If you want to stick to more reputable – but pricey – suppliers, Digi-Key and Mouser have the AD9851 for £31 and the AD9833 for £10

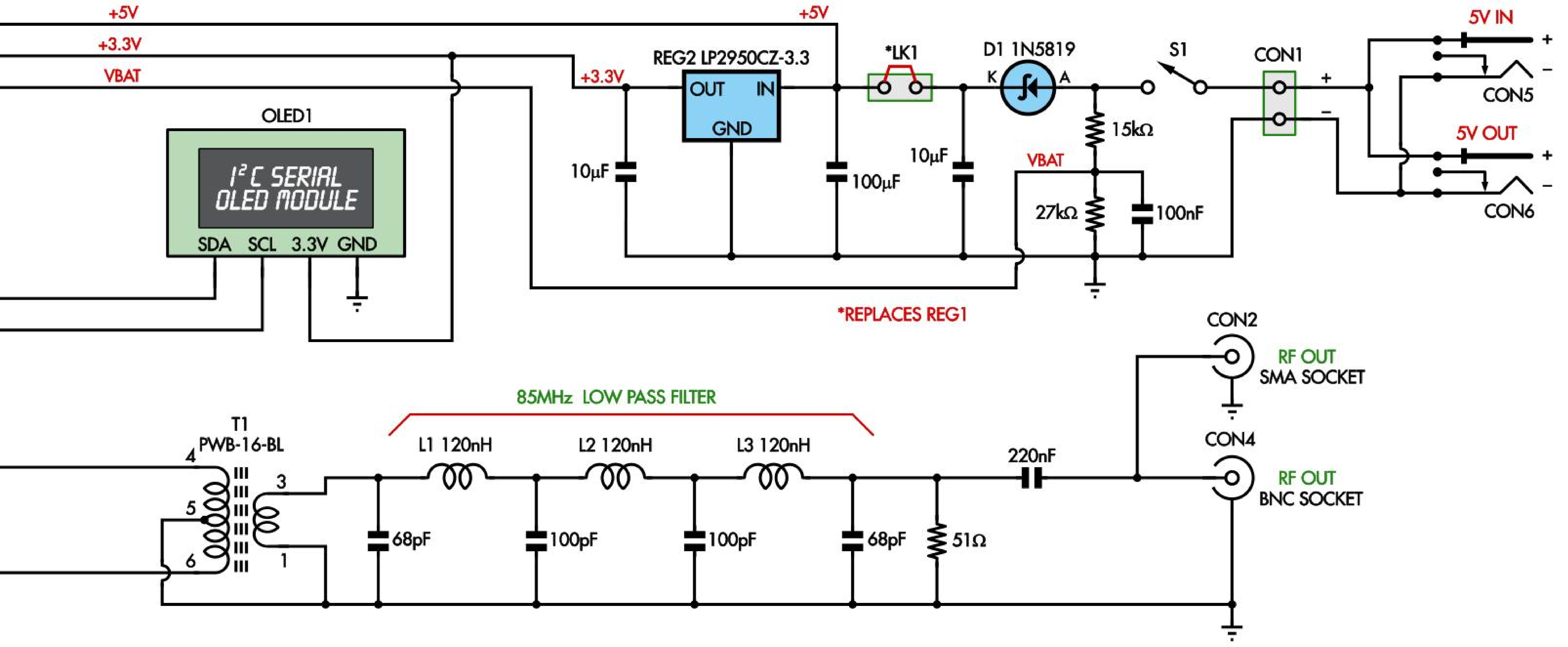
The ATmega644 chip is a little unpredictable and varies enormously in price, ranging from well under £10 to many multiples of that. Mouser and Digi-Key are surprisingly inexpensive but currently out of stock. However, they estimate delivery from May, so they are well worth checking. Wherever you get it, make sure it's the 20MHz, 44-pin TQFP variant.

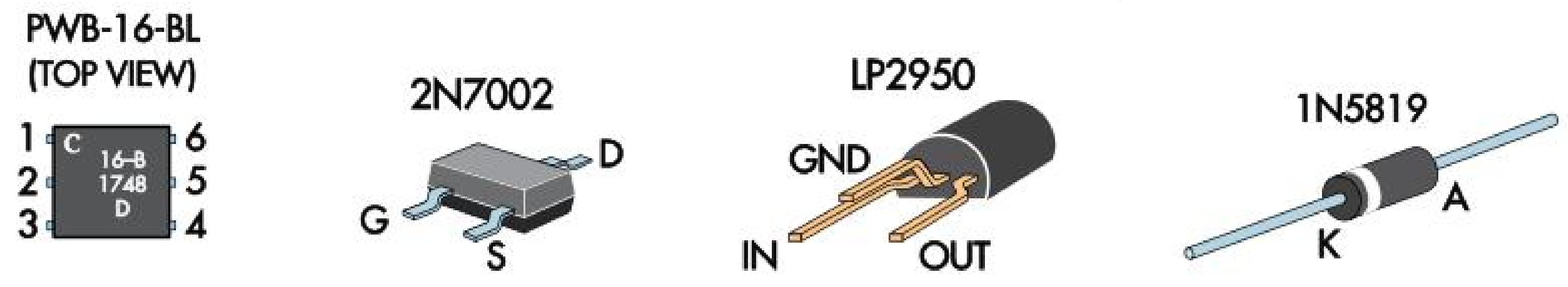
This is quite a sophisticated project and one that is not aimed at beginners. I am assuming that if you are interested in this level of DDS then you know how to program a processor. The board includes a 3x2 ICSP header for you to connect a programmer (AVR ISP) and load the firmware (**CSE21100A.hex**) which is available for download from the May 2023 page of the *PE* website: **https://bit.ly/pe-downloads**

Make sure you read the included text file that describes the fuse values, which need to be set after loading the HEX file (your programming software should have a mode to do that).

The 30MHz TCXO is best obtained from AliExpress, around £13.50 delivered. I have found none suitable at Mouser, Digi-Key or element14.

The OLED is a 0.96in, 128 x 64 pixel type with the SSD1306 controller. There are multiple suppliers for this, and it comes in different colours. The one I have has the top quarter yellow





and the rest blue, and this highlights the set frequency, but you can choose whatever colour combination pleases you.

Likewise, the potentiometers and the encoder are standard items. Make sure that they are the same size. The distance from the PCB to the end of the shaft should be about 25mm.

That leaves the magnetic components. The output transformer is made by Coilcraft, with the PWB-16-BL giving the best result.

M3216/1206-size chip inductors are suitable for the remaining inductors. These have pretty close tolerances, far better than trying to wind your own. At 85MHz, the low-pass filter (LPF) for the RF output needs three 120nH coils. These are readily available at element14, although they can also be sourced from AliExpress. I paid £2 for 100, with free postage, and by some miracle, they arrived from China in two weeks.

The rest of the components are ordinary resistors and capacitors, almost all in the standard M2012/0805 SMD size. The toggle switches can be bought from Jaycar, Altronics and many others, as can the diecast box.

Circuit details

The complete circuit is shown in Fig.1. The microcontroller (IC2) drives the two Analog Devices direct digital synthesis (DDS) chips. The AD9851 (IC3) generates frequencies from 100kHz to 75MHz, while the second DDS chip (IC1, AD9833) provides the amplitude modulation (AM) from 50Hz to 10kHz. The SSD1306 OLED screen (OLED1) shows the current status.

The reference clock for the AD9851 is a 30MHz TCXO which is multiplied by the AD9851 to 180MHz.

The output frequency is adjusted by an incremental shaft encoder (EN1) in steps set by its integral pushbutton switch. Pressing it cycles through step sizes from 1Hz to 1MHz.

Potentiometers VR1 and VR2 are connected to two of IC2's analogue inputs. One sets the modulating frequency for both AM and FM. Rather than have a continuous range of frequencies, I instead opted for 11 separate frequencies. The other adjusts the FM deviation and also for calibration. Three-position toggle switch S2 selects between AM, CW and FM.

Almost everything that I design includes a simplified RS232 serial port using transistors Q2 and Q3. I find this an invaluable tool for debugging while developing the code. It could also be used for controlling the unit from a PC as part of a future upgrade.

The two DAC outputs from the AD9851 are connected to centre-tapped RF transformer T1, which has a 7th-order Chebyshev low-pass filter connected to its secondary to reduce harmonics and spurs.

With a clock frequency of 180MHz, it is possible to generate frequencies up to the Nyquist limit of 90MHz, but the waveform is extremely distorted by then. I set the limit at 75MHz and, with the output filter, it does not contain too many spurs even at that frequency.

The unit draws 140mA from a 5V DC supply. I find that a mobile phone charger is ideal for powering it. I must have at least ten of these; I am sure most people have lots of spares.

As mentioned earlier, the whole thing fits in a standard diecast box, making it quite robust and providing good shielding.

Tuning

The shaft encoder used to adjust the output frequency is available from numerous suppliers on eBay and AliExpress as well as Digi-Key, Mouser, element14 and others. They come in different shaft lengths and prices; choose one with a 20mm shaft length.

I have added pull-up resistors on all the pins. There are weak internal pull-ups in IC2, but I have found the lower value external resistors plus capacitors to ground (for contact bounce filtering) give far more reliable operation.

You want the frequency to increase when you wind the knob clockwise but depending on the shaft encoder, it can operate either way. To solve this, a jumper placed between pins 4 and 6 of the programming header will reverse the encoder direction.

The firmware detects this by enabling a pull-up and checking the level on the MOSI SPI programming pin (PB5, pin 1 of IC2). With the jumper on, this pin is low; otherwise, it is high. The interrupt handler tests the state of the PB5 and selects the rotation direction based on this.

With a range of 100kHz to 75MHz, you don't want to turn the knob millions of times to set the frequency. This is where its integral pushbutton switch comes into use. Pressing it cycles through step sizes of 1Hz, 100Hz, 1kHz, 10kHz, 100kHz and 1MHz.

AD9851 interface

The AD9851 has a 32-bit Frequency Tuning Word (FTW) that controls the output frequency. There is a handy online tool for calculating the required value at: **https://bit.ly/pe-may23-ad**

For a 1MHz output, FTW = 23860929, which is 16C16C1 in hexadecimal. The actual frequency with this FTW is 999.999982305kHz, an error of about 0.02Hz. But this assumes that the TCXO is exactly 30.000000MHz. The ones that I have bought from AliExpress have been within about 10Hz.

Is that good enough? It depends on your application, but with some of the digital communication techniques used, an error of just a few hertz can make message decoding impossible. So I developed a calibration technique that reduces this error to less than 0.1Hz at 10MHz. More on this later.

The FTW can be loaded into the AD9851 using serial or parallel methods. Serial loading takes far too much time and would make FM virtually impossible. Hence, I'm using parallel loading with five bytes transferred: one control byte plus four for the FTW (4 × 8 = 32 bits).

You can see in the circuit diagram that I have split this up into four bits from two separate ports on microcontroller IC2.

I did this because I can't use all of Port A as I need two analogue inputs, and the only available analogue inputs are on Port A. Port B has the 20MHz clock output required by the AD9833 (PB1), so that's ruled out. Port C has dedicated SDA and SCL pins for the I^{2}C interface to the OLED, and I want to use INT0 and INT1 on port D for the shaft encoder.

Therefore, I couldn't dedicate all eight lines of one port for loading the FTW. So I split up the parallel interface into four bits from Ports C and D. The extra few lines of code required to do this don't slow things down very much. Once the byte is set up, it is clocked in by the WCLK pin, and after all five bytes have been sent, the FQUD pin is pulsed to update the AD9851's internal latch.

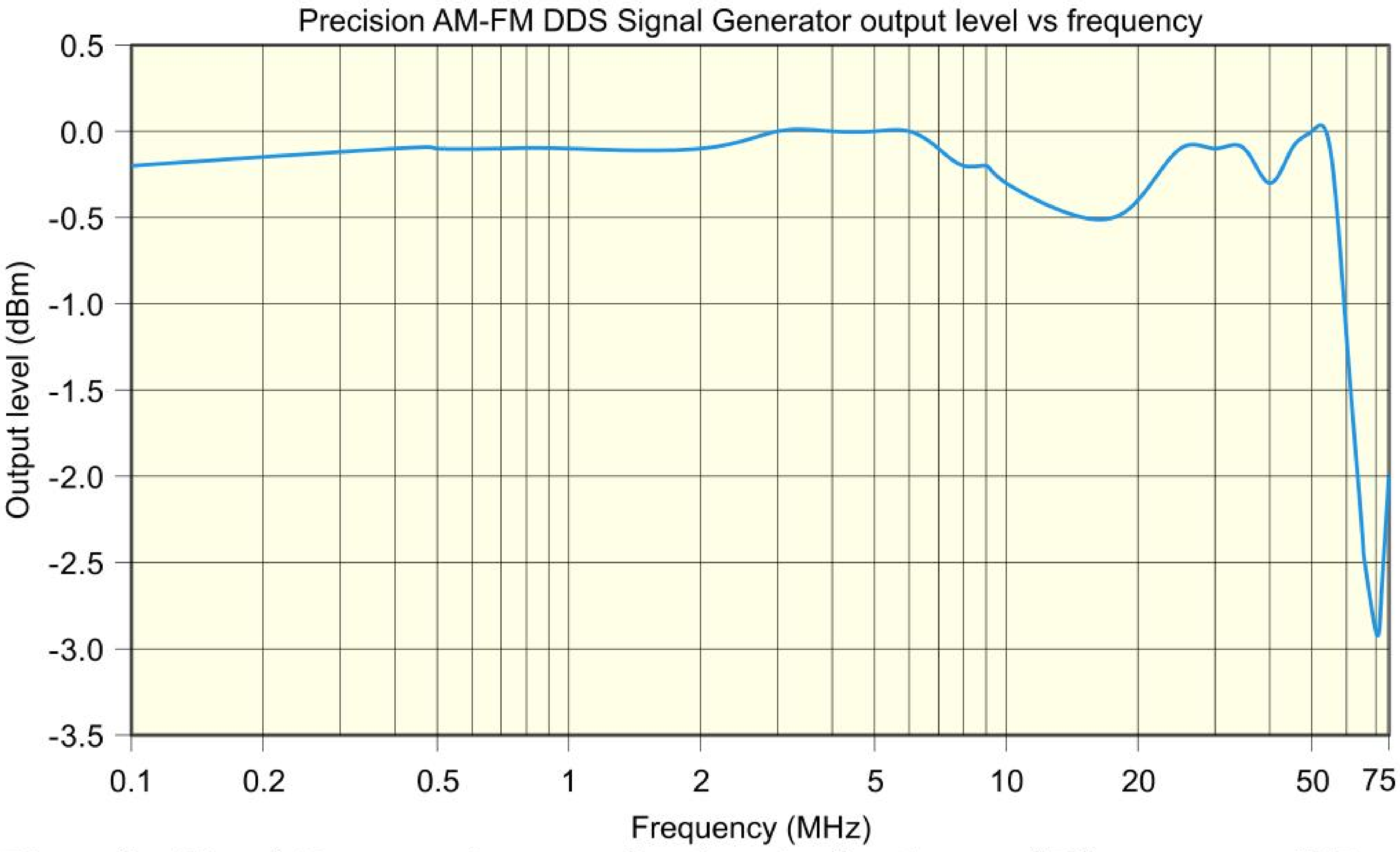


Fig.2: the Signal Generator's output level varies by about ¼dB between 100kHz and 55MHz, except for a dip at –½dB between about 10MHz and 22MHz. It's usable up to 75MHz, although the level drops considerably above 55MHz, reaching nearly –3dB at 70MHz.

RF output

There are two outputs from the DAC (digital-to-analogue converter) on the AD9851. Application note AN-423 from Analog Devices suggests using a wideband transformer to couple these two outputs to the external load. This makes for clean amplitude modulation (AM), also described in the note.

The transformer in their example is 1:1 centre tapped, which for a 50Ω load, reflects 25Ω to the DAC outputs.

I used a Coilcraft transformer with this ratio and found it to be most unsatisfactory. The 25Ω load on the DAC outputs is far too low in impedance; it reduced the output levels, and the waveform became very noisy. I feel that specifying such a transformer is an error.

Experimenting with other Coilcraft transformers, I found the best results were with the PWB-16-BL with a 16:1 impedance ratio that reflects 400Ω to each DAC output; a far more satisfactory value. The transformer –3dB bandwidth is 75kHz to 90MHz, so there is a slight drop in level at 100kHz and 75MHz. This gave me an output close to 0dBm over much of the range (Fig.2).

Output Filter

Without a low-pass filter on the output, there will be many undesirable harmonics and spurs. While it is feasible to use some of these spurs for frequencies well above the Nyquist limit, for simplicity, I decided not to use this approach.

Filter design is so easy these days. Rather than ploughing through some complex s-parameter mathematics, there are online calculators. The one I used to work out the *C* and *L* values for a 7th-order Chebyshev low-pass filter with 85MHz cutoff and 0.5dB passband ripple is at: **https://rf-tools.com/lc-filter/**

The output of this calculator can be exact or standard values; the difference in performance between the two is minimal. The choice of inductors was discussed above in the component selection section.

Amplitude modulation

The ATmega644 processor (IC2) could generate amplitude modulation, but

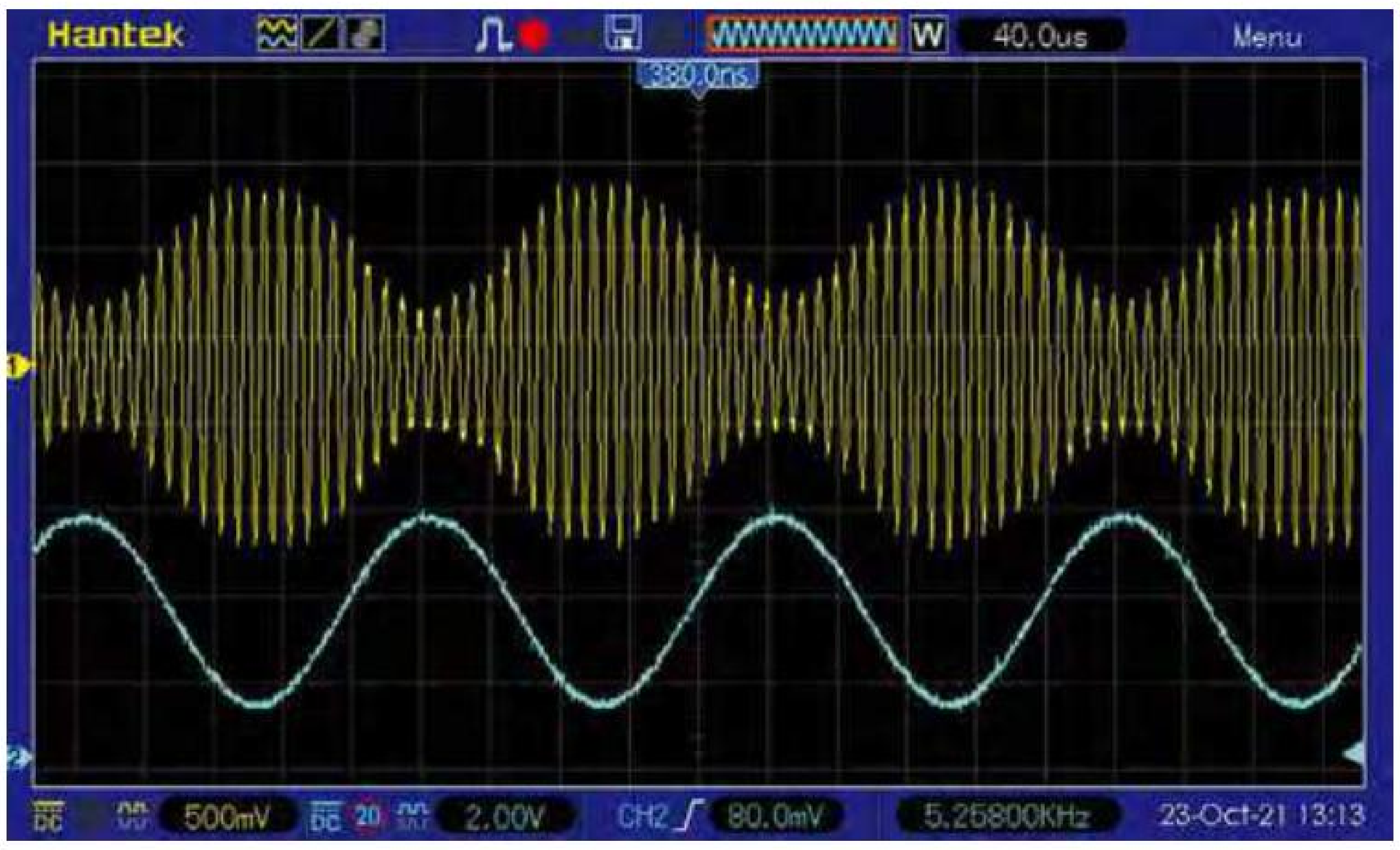


Fig.3: here's what the 100kHz output signal looks like with 5kHz AM (yellow). The AM signal output from the AD9833 is shown below (cyan).

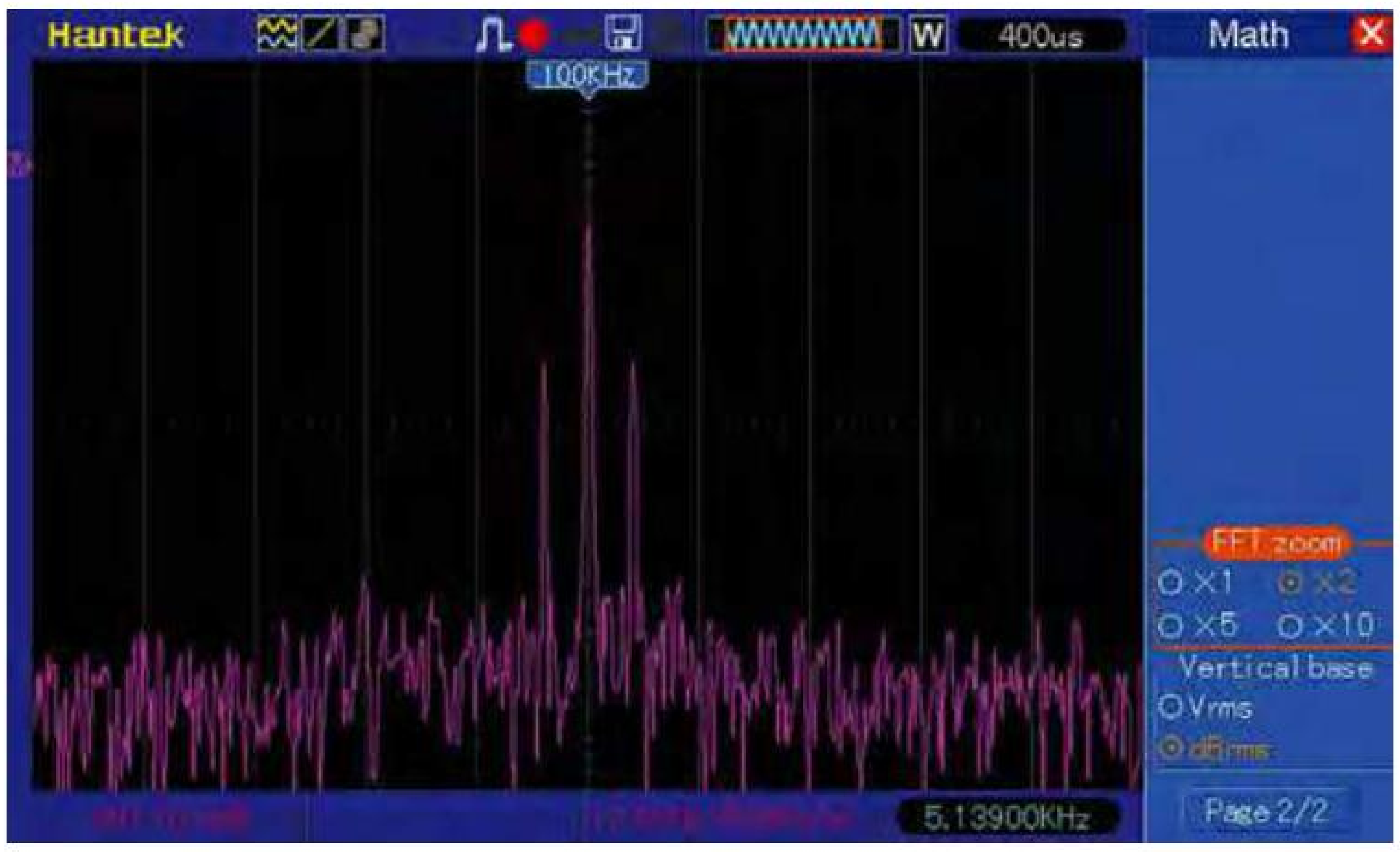


Fig.4: as expected, the spectrum of the signal from Fig.3 has a single prominent peak at 100kHz with two smaller peaks, 5kHz on either side (ie, at 95kHz and 105kHz).

why bother with the complicated coding involved when we can use a second low-cost DDS chip instead? The AD9833 (IC1) can run at clock speeds of up to 25MHz. It is a tiny 10-pin chip with a three-wire serial control interface.

Rather than having a separate clock generator, I use the 20MHz clock out pin on PB1 (pin 41) of IC1. The output of the AD9833 is applied to the gate of MOSFET Q1 via a 10kΩ trimpot, and this controls the RSET pin on the AD9851 as per the aforementioned application note AN-423. Rather than having a separate knob on the front panel, I preset the modulation level to about 50%.

Potentiometer VR1 sets the modulation frequency. The voltage read using the 10-bit analogue-to-digital converter (ADC) in IC2 is converted by software into the tuning word required by the AD9833.

I could have had a continuous range but found that setting the frequencies was very fiddly. I decided instead on dividing the ADC reading into 11 distinct values: 50Hz, 100Hz, 200Hz, 400Hz, 1kHz, 2kHz, 3kHz, 5kHz, 6kHz, 8kHz and 10kHz.

Fig.3 shows a 100kHz generated signal with 50%, 5kHz amplitude modulation on channel 1, with the sinewave modulation signal on channel 2. The spectrum of this signal is shown in Fig.4.

Frequency modulation

Applying FM proved to be the trickiest part of the design. To approximate a sinewave, we have to change the AD9851 output frequency continuously. This sinewave is divided into 24 samples, each 15° apart. Taking the sine of that angle and multiplying it by the maximum deviation gives the instantaneous deviation for that sample.

For example, if the maximum deviation is 3kHz, $\sin(30°) = 0.5$, so we add a value to the FTW equivalent to 1.5kHz (3kHz x 0.5). The numbers become negative past 180° and subtract from the frequency. This takes quite a bit of processor time; so much that the maximum modulation frequency possible is 1000Hz.

At this frequency, the microcontroller's timer generates 24,000 interrupts per second, and each triggers a new FTW value to be calculated and sent. For other modulation frequencies, the timer interrupt is 24 times the modulation frequency. See Table 1 for the values that are added and subtracted to the FTW to give ±2.5kHz deviation.

The available modulation frequencies are 50Hz, 100Hz, 200Hz, 400Hz, 500Hz, 600Hz, 700Hz, 800Hz, 900Hz and 1kHz.

There are ways of getting a higher modulation frequency. If we can stand having a rougher sinewave, we could have samples 30° apart, which would allow a maximum frequency of 2kHz.

The spectrum of an FM signal is far more complex; advanced mathematics is needed to derive it. It has sidebands that go on forever, but their amplitude decreases rapidly so that only the first few are important. For more details visit: **https://w.wiki/4eC$**

Display

The OLED module has an SSD1306 controller and a resolution of 128 x 64 pixels.

My original design used an 8 x 8 font which gave eight lines each of 16 characters. This allowed for a fair bit of information to be displayed but with rather tiny characters. I changed it to a 16 x 16 font, which is much easier to read, but this gives only four lines of eight characters. So I had to considerably simplify what is displayed.

Screen 1 shows the unit's normal display. The top line readout is the frequency in Hz, while the second has the frequency adjustment step size. Line 3 shows the AM frequency, one of 11 fixed frequencies from 50Hz to 10kHz. Line 4 shows the FM frequency, which steps through 11 fixed settings from 50Hz to 1kHz.

With the Function knob fully clockwise, the unit enters calibration mode, shown in Screen 2. The modulation frequencies are replaced with line 3 showing 'Calib' and line 4 showing the Frequency Tuning Word (FTW). The calibration procedure is explained later in the article.

Power supply

Many readers will have numerous mobile phone chargers lying around, left over from generations of phones. Most of them deliver a nominal 5V at up to 2A. The maximum current drawn by the *Generator* is about 140mA, well within the capability of all chargers.

I included a schottky diode in the design for reverse polarity protection. This drops the supply voltage by about 0.37V. The charger that I used had an output of 5.2V, dropping to 4.85V through the diode. It's a simple matter of cutting off the connector on the cable and replacing it with a DC barrel plug to suit your DC socket (either 2.1mm or 2.5mm inner pin diameter).

The PCB design includes another regulator, REG1, so that a higher supply voltage could be used. However, this is probably not necessary, so it's just linked out in the final design.

I have connected another DC socket, CON6, in parallel with CON5. This is for powering the companion *Attenuator*, to be described in a future article.

The OLED requires 3.3V, and this is supplied by a TO-92 low-dropout linear regulator, which draws from the 5V supply. The open-drain SDA and SCL pins for driving the OLED are pulled up to 3.3V by a pair of 4.7kΩ resistors.

Construction

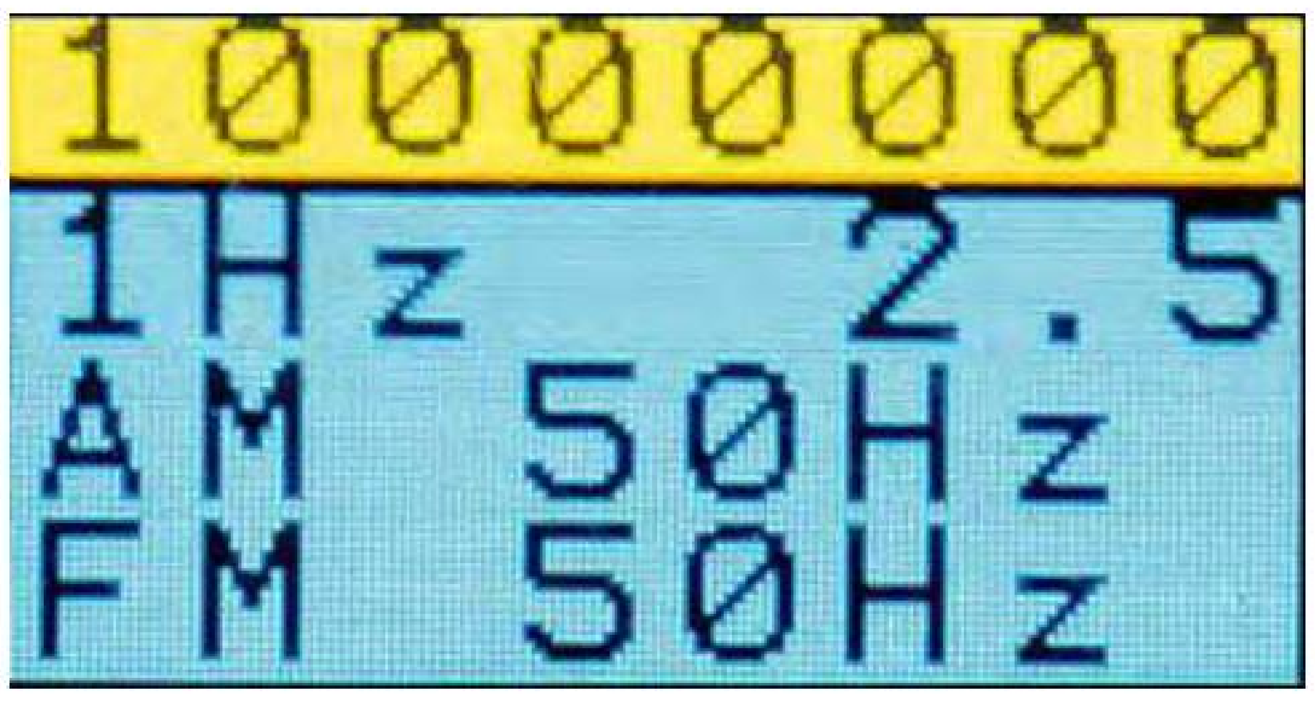
The *Signal Generator* is built on a double-sided PCB coded CSE211002 that measures 100 x 78.5mm and is available from the *PE PCB Service*. Refer to the PCB overlay diagram (Fig.5) as a guide during construction. It shows which components go where.

Most of the parts on the PCB are surface-mount types, and two of them are very fine-pitch ICs. These are the two DDS chips, and you should start with these. Soldering them accurately and without short circuits between the pins takes some skill.

It helps to spread a little flux paste on the pads before placing the ICs and ensure they are aligned with their pads

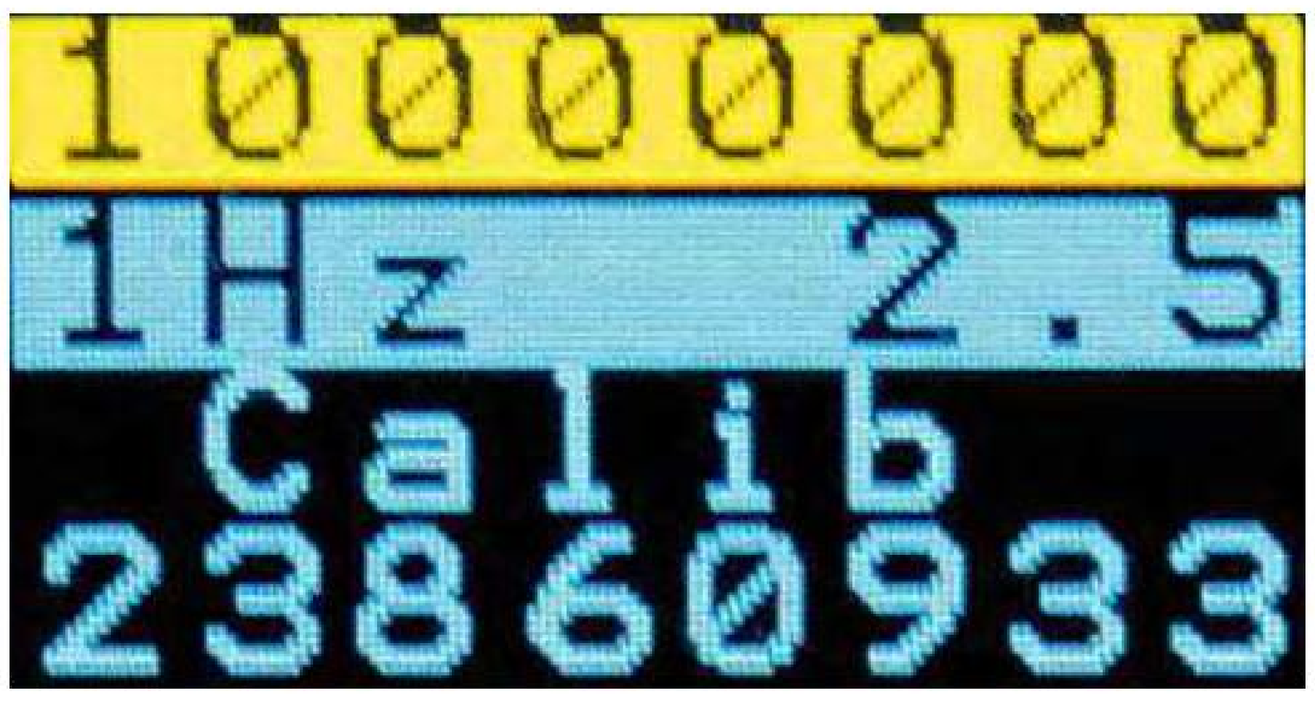
Table 1 – frequency modulation FTW offsets for ±2.5kHz deviation

angle θ	sin(θ)	Δf (Hz)	ΔFTW
0°	0	0	0
15°	0.259	647	15,437
30°	0.500	1250	29,825
45°	0.707	1767	42,160
60°	0.877	2192	52,301
75°	0.966	2415	57,622
90°	1.000	2500	59,650
105°	0.966	2415	57,622
120°	0.877	2192	52,301
135°	0.707	1767	42,160
150°	0.500	1250	29,825
165°	0.259	647	15,437
180°	0	0	0
195°	-0.259	-647	-15,437
210°	-0.500	-1250	-29,825
225°	-0.707	-1767	-42,160
240°	-0.877	-2192	-52,301
255°	-0.966	-2415	-57,622
270°	-1.000	-2500	-59,650
285°	-0.966	-2415	-57,622
300°	-0.877	-2192	-52,301
315°	-0.707	-1767	-42,160
330°	-0.500	-1250	-29,825
345°	-0.259	-647	-15,437



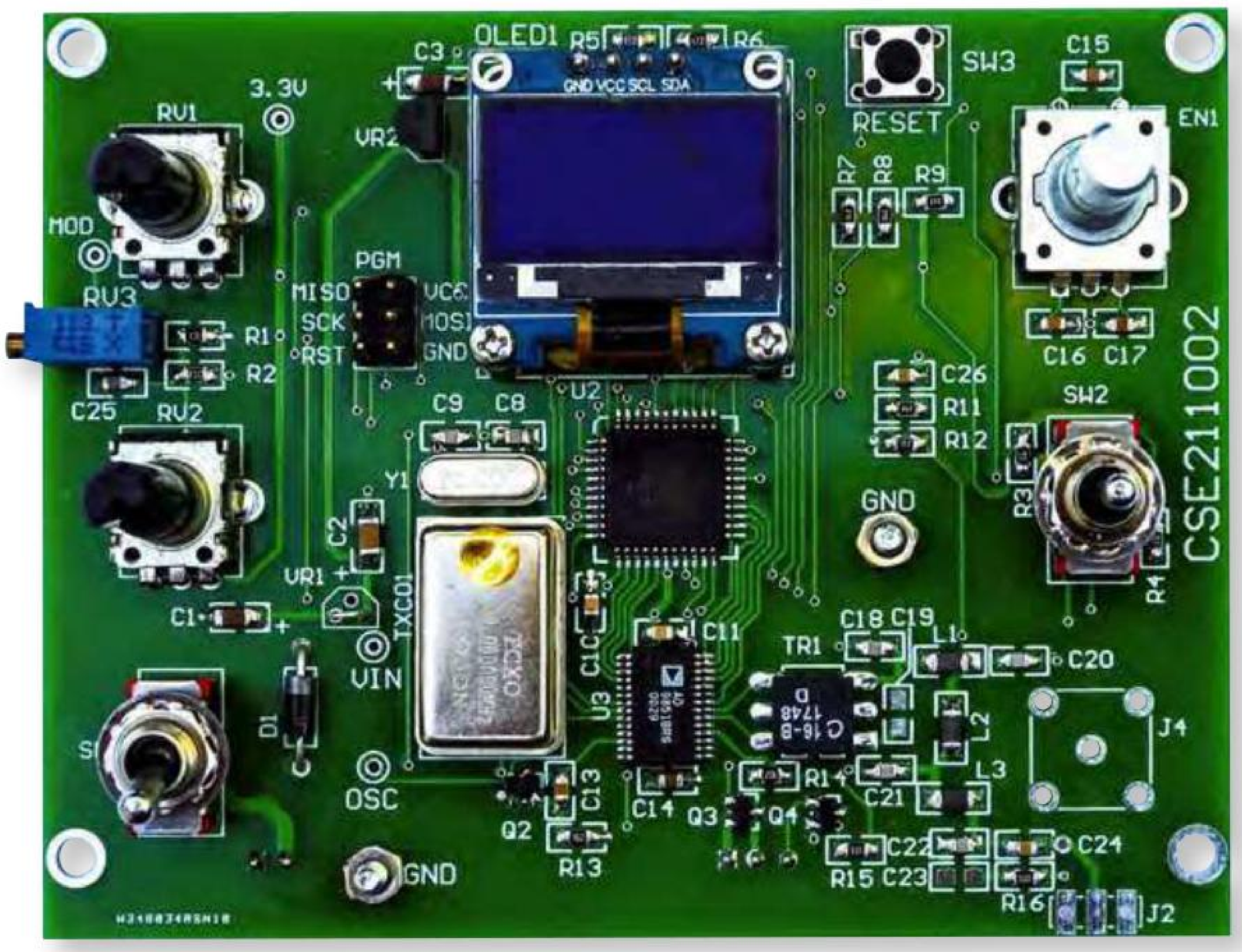
```
10000000
1Hz   2.5
AM  50Hz
FM  50Hz
```

Screen 1: this shows the screen layout during normal operation. The output frequency (in Hz) is at the top, the step size and FM deviation on the second line and the amplitude and frequency modulation signal frequencies on the last two lines.



```
10000000
1Hz   2.5
  Calib
23860933
```

Screen 2: calibration mode is entered by rotating the Function knob fully clockwise; the bottom two lines of the display change, with the last line showing the FTW. If you have the right gear, you can get the output frequency within 0.1Hz.


OLED1
R5
R6
C3
3.3V
RV1
VR2
SW3
RESET
C15
EN1
MOD
RV3
PGM
MISO
SCK
RST
R1
R2
C25
RV2
C9
C8
U2
Y1
R7
R8
R9
C16
C17
C26
R11
R12
SW2
CSE211002
GND
C2
VR1
TXCO1
C1
VIN
D1
S1
OSC
U3
C13
C14
C11
TR1
C18
C19
L1
C20
L2
L3
J4
R14
C21
Q2
Q3
Q4
R13
C22
C23
C24
R15
R16
J2
GND

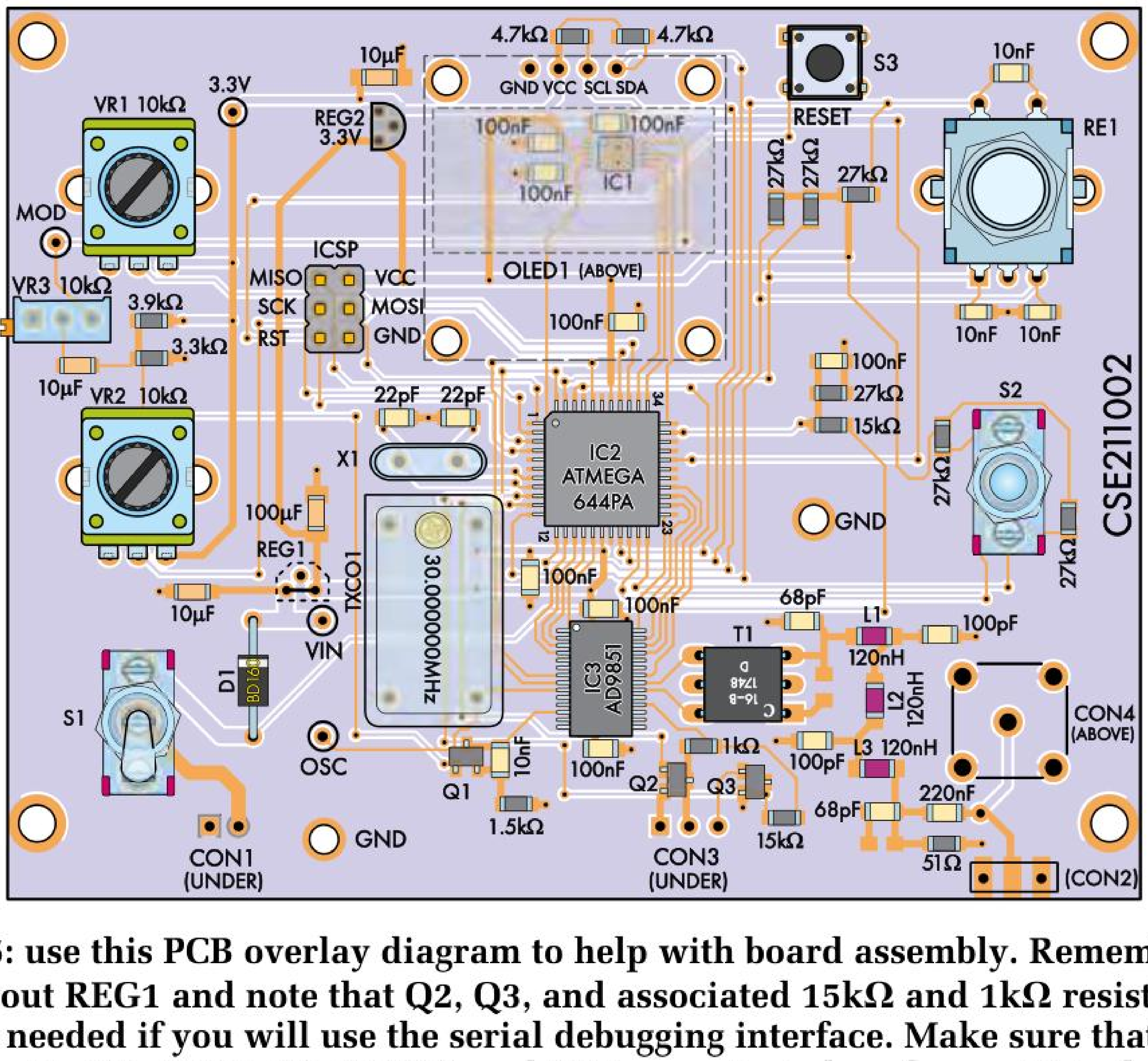

4.7kΩ
4.7kΩ
GND VCC SCL SDA
S3
RESET
10nF
RE1
10µF
3.3V
VR1 10kΩ
REG2 3.3V
100nF
100nF
100nF
IC1
27kΩ
27kΩ
27kΩ
MOD
ICSP
OLED1 (ABOVE)
VR3 10kΩ
MISO
SCK
RST
VCC
MOSI
GND
3.9kΩ
3.3kΩ
100nF
10nF
10nF
10µF
VR2 10kΩ
22pF
22pF
100nF
27kΩ
15kΩ
S2
X1
IC2 ATMEGA 644PA
27kΩ
CSE211002
GND
27kΩ
100µF
REG1
TXCO1
30.000000MHz
10µF
100nF
100nF
68pF
L1
100pF
T1
120nH
D1
VIN
IC3 AD9851
L2 120nH
S1
CON4 (ABOVE)
OSC
10nF
1kΩ
L3 120nH
100pF
Q1
100nF
Q2
Q3
220nF
68pF
1.5kΩ
15kΩ
51Ω
CON1 (UNDER)
GND
CON3 (UNDER)
(CON2)

Fig.5: use this PCB overlay diagram to help with board assembly. Remember to link out REG1 and note that Q2, Q3, and associated 15kΩ and 1kΩ resistors are only needed if you will use the serial debugging interface. Make sure that the three ICs, D1, REG2, T1, TCXO1 and VR1 are oriented as shown. Note that the orientation of REG2 is swapped in the prototype, this is because regulator that was used has a different pinout than the one specified in the parts list.

on both sides after tacking the first pin and before soldering any others. Also, be careful to check that their pin 1s are located correctly before soldering more than one pin!

Rather than trying to solder the pins without bridges, concentrate on making sure that each pin gets enough solder and that it flows down onto the corresponding PCB pad. Try to avoid getting any solder high up on the pins, where it is harder to fix bridges.

After soldering all the pins, it's then just a matter of spreading some more flux paste over them and carefully using a length of solder wick to remove any excess solder, including that which might be bridging adjacent pins. Clean off the flux residue with some flux cleaner or alcohol, then inspect the IC leads to make sure all the solder joints look good and there are no remaining bridges.

If you find anything that looks suspect, add a dab of flux paste, heat the offending pin(s) and use solder wick if necessary. Repeat this process as many times as needed until you have nicely soldered ICs.

Following these, mount the ATmega644 chip (with wider pin spacings than the first two, but pins on four sides), again being careful with its pin 1 orientation, followed by all the other SMD components. The orientation of SMD transformer T1 also matters. Then give the board a good clean to remove flux residue.

Now fit the through-hole parts from lowest profile to tallest. Be careful to orientate diode D1, the TCXO, VR3, and REG2 as shown. Don't forget the wire link across REG1, which can be made from a component lead off-cut.

You can safely omit Q2, Q3, the two adjacent resistors and CON3. These are the simplified RS232 interface and are used as a debugging aid.

The OLED screen plugs into a four-pin socket strip and is held in place by two screws and standoffs. Rather than cutting down an 8-pin strip that I already had, I just removed four pins.

Depending on the OLED, the mounting holes may be either 2mm or 2.5mm in diameter. While M2 screws are not as easy to find as M3, I bought some from eBay. Some larger online electronics retailers also stock M2 screws and nuts. Don't try to drill the holes out on the OLED to bigger screw sizes! There are four screw holes provided but two are adequate.

The potentiometers and encoder should be installed last, after cleaning off any flux residue on the board.

Preparing the case

The photo (overleaf) shows the diecast box with the board already mounted in the base. The positions of the required holes are shown in the drilling and cutting template/guide, Fig.6.

The case's raw aluminium is not very attractive, so I sprayed it with three coats of matte black paint. I used the blank circuit board as a template to accurately drill the mounting holes and the holes for the control shafts. There are small holes on the PCB in the centre of the controls for this purpose.

It takes a bit of care to make the rectangular cutout. There are various ways of doing it. If you have a milling machine, that's great, but very few readers would possess one. I started by drilling a circular hole of 25mm diameter centred on the rectangle with a step drill. Then I filed it out into the required 26 x 28mm rectangle. It takes a bit of time but results in a neat finish.

You will also need to drill two holes in the side of the base, near the lid, to accept the barrel sockets. Make sure they are placed so that they will not foul the PCB assembly once it's dropped in. You might also want to drill a hole in the side so that you can access VR3 (the AM depth adjustment trimpot) once the board has been mounted in the case.

The panel label shown in Fig.7 can be downloaded from the May 2023 page of the *PE* website and printed onto photographic paper – visit: **https://bit.ly/pe-downloads**

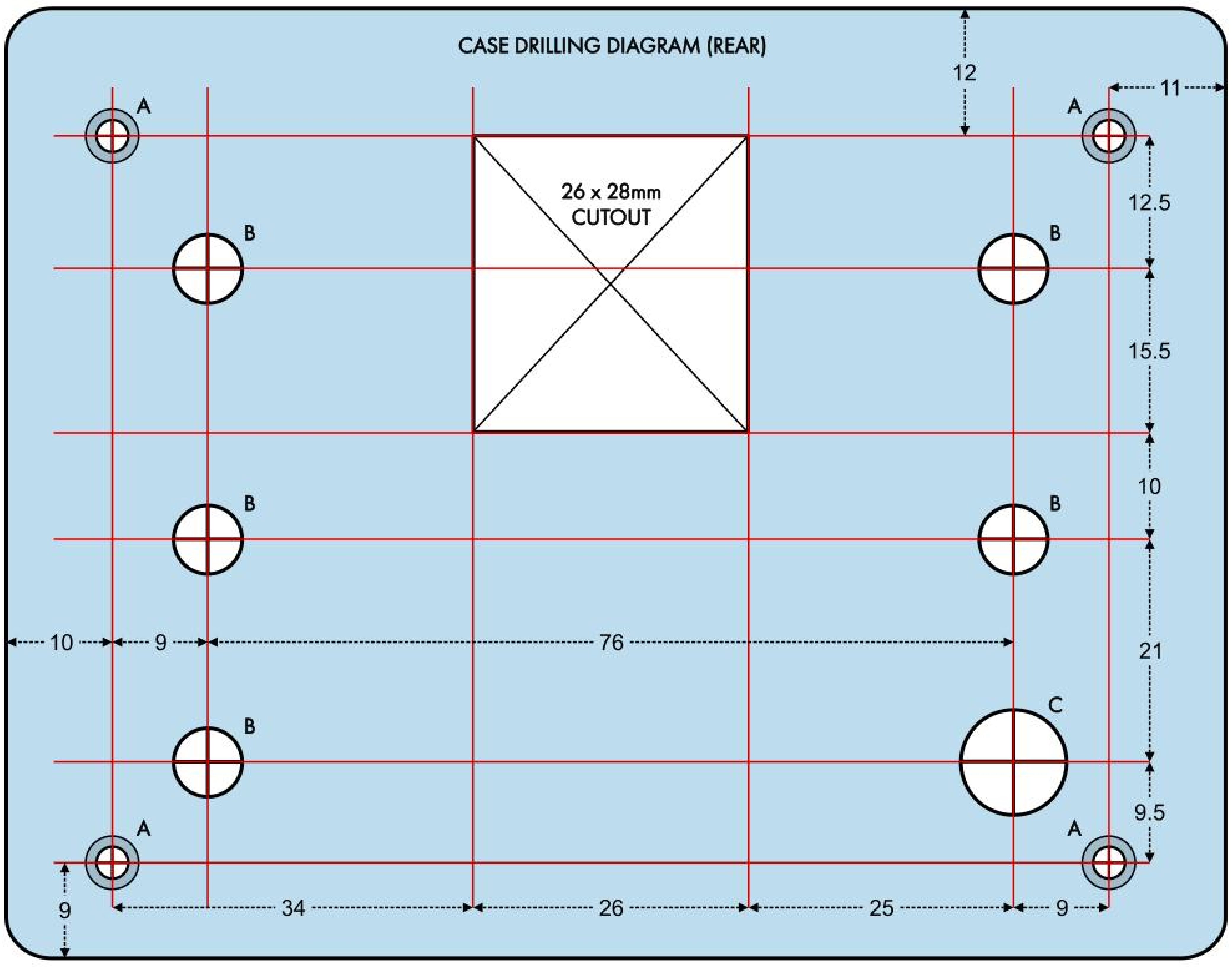
Make the OLED and shaft cutouts with a sharp scalpel or hobby knife. I cut a piece of 1mm-thick clear acrylic to 112 x 86 mm to protect the label, again using the blank PCB as a template to drill the holes.

Attach the PCB to the front panel using 12mm threaded spacers with countersunk screws on the outside. Add a washer under each spacer to slightly increase the distance.

Now it's time to install the panel-mount connectors. It turned out to be too difficult to mount the BNC connector on the PCB itself. Connect a 50mm length of stiff wire to the connector and pass this through the centre hole of the BNC connector location on the PCB. Once the board is attached to the box, cut off the excess and solder it. To remove the board, you will have to desolder this one wire.

After the PCB has been fitted, connect the DC sockets in parallel, then wire them to the matching plug for CON1. Make sure the wires are the right length to reach CON1. Also, ensure the polarity is correct. You can check this by testing for continuity between the barrel socket's tip and one end of power switch S1, and also continuity from the outer barrel (with a plug inserted) to PCB ground.

Apply power and check that everything works before fitting the lid to the box with the supplied screws. You should get a sensible display on the OLED as soon as it's switched on. Check that you can adjust all the parameters with the knobs.



ALL DIMENSIONS IN MILLIMETRES

HOLE A : 3mm diam., CSK
HOLE B : 6.5mm diam.
HOLE C : 10.0mm diam.

Fig.6: template of the cutouts on the diecast box. This template can be downloaded from the PE website and printed at actual size. You can also use the blank PCB to mark the hole positions.

If you run into any problems, remove the PCB and have a good look at it. Check that all the solder joints look good, especially on the SMDs, and that everything is where it should be, referring to Fig.5.

Calibration

Without calibration, the accuracy of the signal generator is entirely dependent on the TCXO. The best calibration procedure requires a two-channel oscilloscope, a GPS-disciplined 10MHz reference and a high-precision frequency counter (which might be built into some higher-end oscilloscopes).

Set the three-position switch to 'CW' and the output frequency to 10000000Hz (10MHz). Rotate the Function knob fully clockwise and adjust the tuning knob to get FTW = 23860929. This is the value needed if the TCXO has an output of precisely 30MHz. If you have no other equipment available, press the tuning button to save that value into EEPROM and turn the Function knob back a bit.

If you have an accurate frequency counter, repeat above but adjust the FTW for exactly 10MHz on the

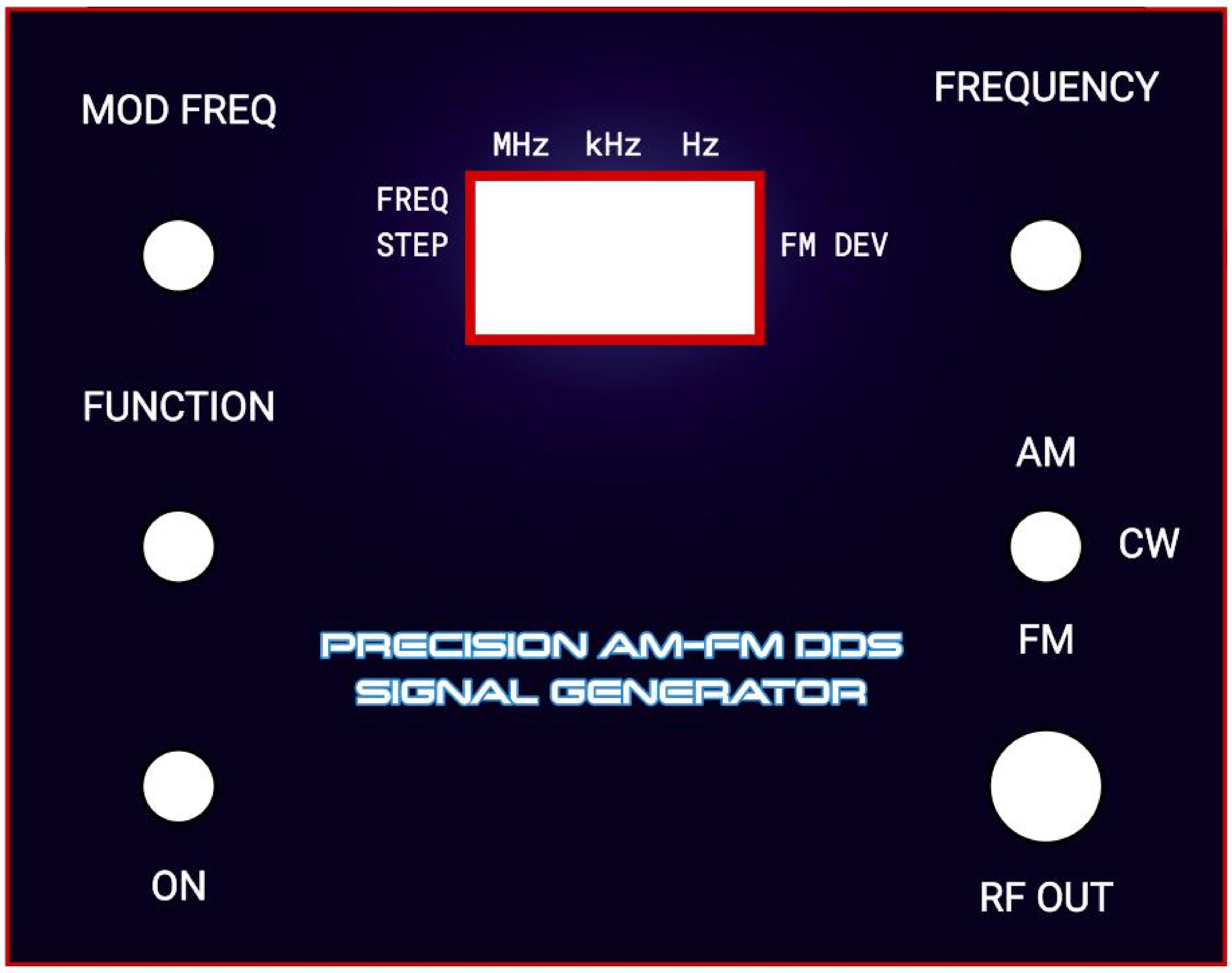
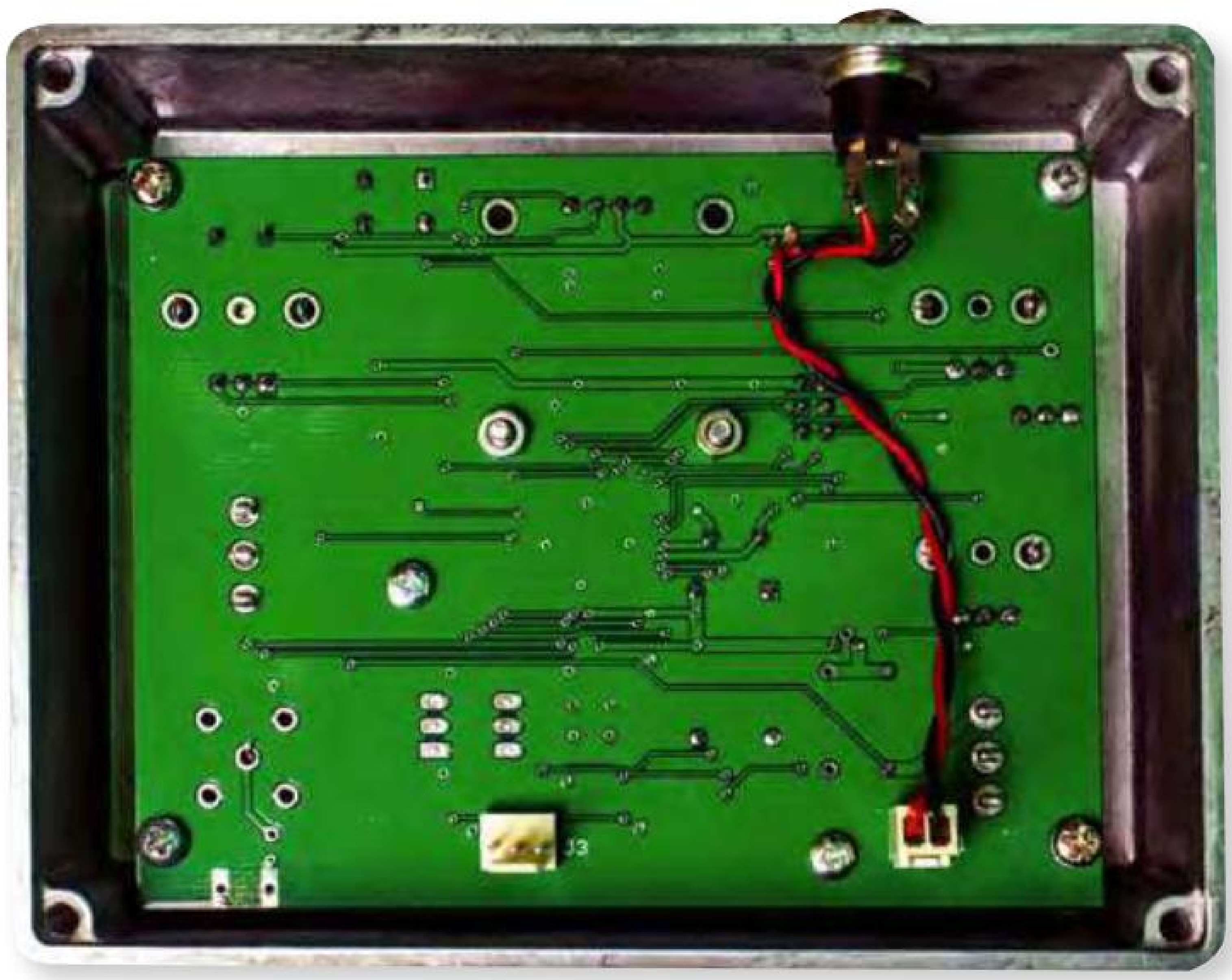


Fig.7: the front panel label for the Precision DDS Signal Generator.



Once the PCB has been mounted in the case and the wire to the BNC socket soldered, all you need to do is wire up and plug in the DC socket. You only need one, as shown here, but if you're thinking of building the upcoming matching attenuator, add a second socket in parallel so you can daisy-chain the power.

Atten
26 dB
Step 5
J2 INPUT
CSE211003 Attenuator
J3 OUTPUT

A 'sneak peak' at the companion attenuator PCB that we will describe in an upcoming issue.

frequency counter, and save it into EEPROM as before.

For best accuracy, first, adjust the frequency using the counter as above. Then connect the GPS disciplined reference 10MHz signal to one channel of a two-channel oscilloscope, and trigger on that channel to produce a stationary display. Set the signal generator to 10MHz and connect it to the other scope channel.

If the frequencies are identical, the signal generator waveform will be steady. But this will hardly ever be the case; it will drift left or right. Set the Function knob fully clockwise, and using the tuning knob, adjust the FTW for minimum drift. Typically, the drift will take 10 or more seconds across one complete cycle. The 10 seconds corresponds to an error of 0.1Hz at 10MHz. Press the frequency button to save the calibrated FTW value into the EEPROM.

The calibrated frequency may hold for several hours depending on temperature fluctuations; the TCXO is by no means perfect. Do the calibration just before you want to do any seriously accurate work.

There is a multi-turn trimpot accessible through a hole in the left side of the case. Setting the amplitude modulation level is best done using an oscilloscope. Still, if you loosely couple the output to an AM receiver, you can simply adjust the level for a clear tone. It will overmodulate and create lots of spurious and harsh harmonics if you wind it up too much.

A matching attenuator

In the small enclosure I specified it was impractical to fit an attenuator

Parts List – AM-FM DDS Signal Generator

1 PCB coded CSE211002, 100 x 78.5mm available from the PE PCB Service
1 diecast aluminium enclosure, 119 x 93.5 x 34mm **[Jaycar HB5067 or Altronics H0454]**
1 0.96in OLED display module with I^{2}C interface and SSD1306 controller (OLED1)
1 mechanical rotary encoder with integrated pushbutton switch and 20mm total height (RE1) **[Bourns PEC11R-4215F-S0024]**
2 10kΩ PCB-mount vertical 10mm 20mm-tall linear potentiometers (VR1, VR2) **[Alpine RK09K1130AH1]**
1 10kΩ side-adjust multi-turn trimpot (VR3) **[Altronics R2361]**
1 large knob to suit RE1
2 medium knobs to suit VR1 and VR2
1 20MHz 18pF 30ppm crystal resonator, HC-49 (X1)
1 30MHz 20 x 12mm TCXO module (TCXO1) **[aliexpress.com/item/32719087266.html]**
1 Coilcraft PWB-16-BL SMD wideband transformer (T1)
3 Coilcraft 1206CS-121XJEC 120nH chip inductors or equivalent, M3216/1206 size (L1-L3)
1 3x2 pin header, 2.54mm pitch (ICSP) (**optional**; for programming IC1)
1 2-pin polarised locking header with matching plug, 2.54mm pitch (CON1)
1 3-pin polarised header with matching plug, 2.54mm pitch (**optional**; CON3)
1 panel-mount BNC socket (CON4)
2 panel-mount DC barrel sockets (CON5, CON6)
1 4-way female header socket (for OLED1)
1 SPDT panel-mount switch (S1) **[Altronics S1310]**
1 SPDT panel-mount centre-off switch (S2) **[Altronics S1330]**
1 tactile pushbutton switch (S3)
4 12mm-long M3 tapped metal spacers
2 10mm untapped spacers
4 M3 x 6mm panhead machine screws
4 M3 x 8mm countersunk head machine screws
2 M2 x 12mm panhead machine screws and nuts
4 M3 flat washers

Semiconductors
1 AD9833 12.5MHz DDS generator, MSOP-10 (IC1)
1 20MHz ATmega644 microcontroller in TQFP-44 (eg, ATMEGA644PA-AN or ATMEGA644PA-AU) programmed with CSE21100A.hex (IC2)
1 AD9851BRS 180MHz DDS generator, SSOP-28 (IC3)
1 LP2950CZ-3.3 3.3V low-dropout linear voltage regulator, TO-92 (REG2)
3 2N7002 60V 2A N-channel 3.3V drive MOSFETs, SOT-23 (Q1-Q3)
1 1N5819 40V 1A schottky diode (D1)

Capacitors *(all SMD M2012/0805 size unless otherwise stated)*
1 100µF 6.3V X5R ceramic, M3216/1206 size
3 10µF 6.3V X5R ceramic
1 220nF 50V X7R ceramic
10 100nF 50V X7R ceramic
2 10nF 50V X7R ceramic
2 100pF 50V NP0/C0G ceramic
2 68pF 50V NP0/C0G ceramic
2 22pF 50V NP0/C0G ceramic

Resistors *(all SMD M2012/0805 size 1% thick film unless otherwise stated)*
6 27kΩ
2 15kΩ
2 4.7kΩ
1 3.9kΩ
1 3.3kΩ
1 1.5kΩ
1 1kΩ
1 51Ω

into the same housing. Therefore, I have designed a separate attenuator in another identical enclosure with an attenuation range from 1dB to 110dB in 1dB steps. As the output of the *Signal Generator* is about 0dBm, this means the lowest signal level that the pair can generate is around –110dBm. The photo on the previous page shows a preview of the attenuator, to be described in an upcoming article.

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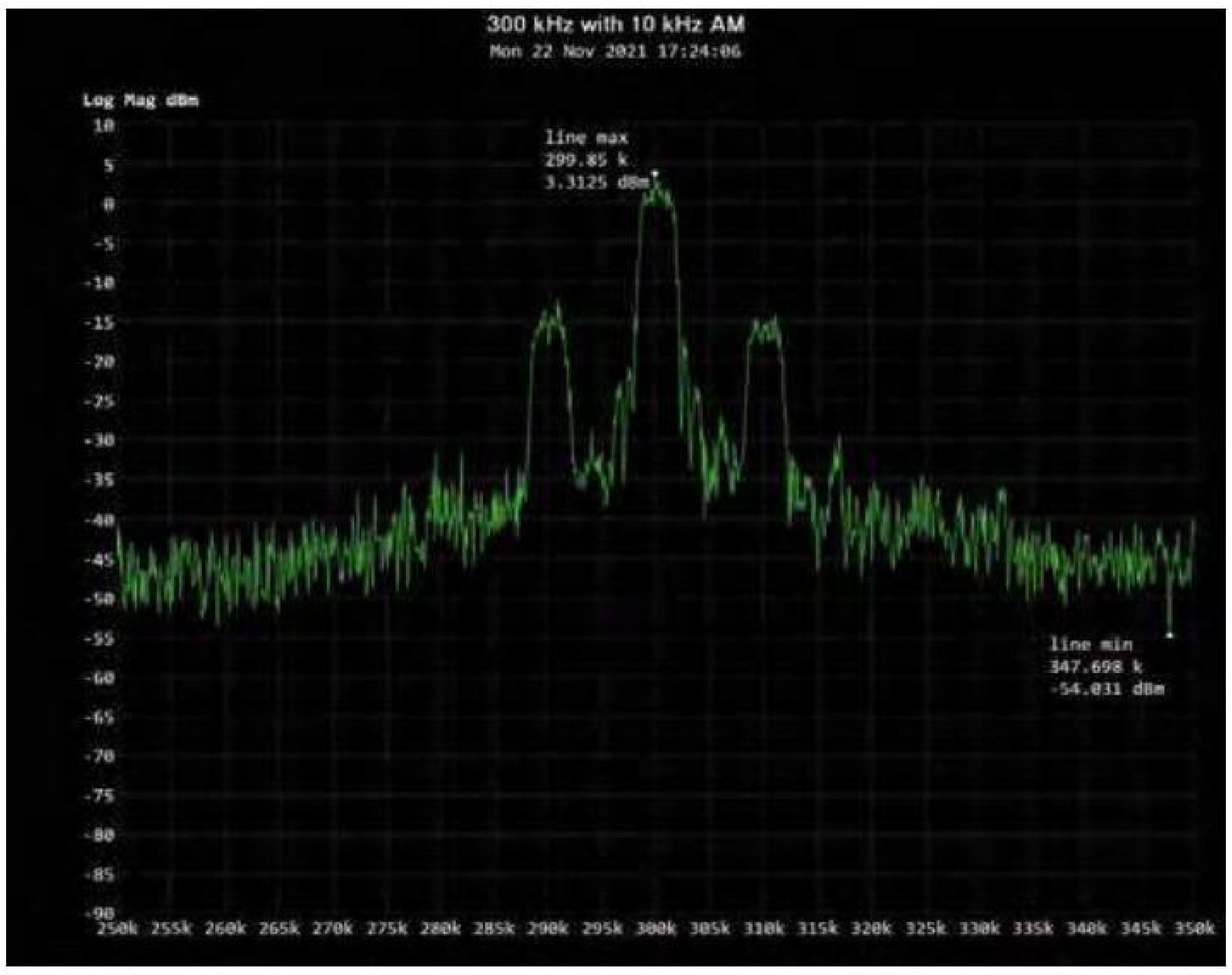
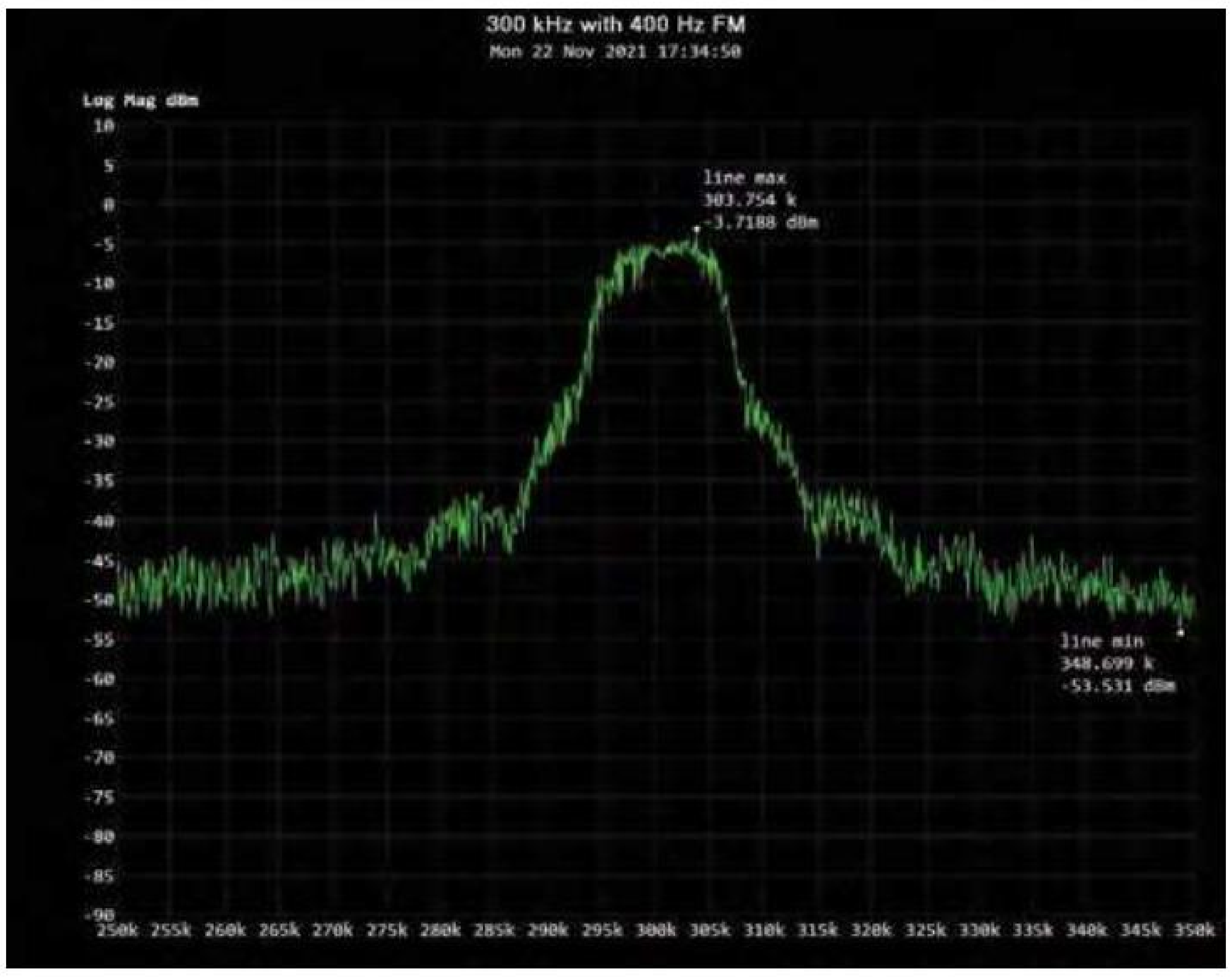
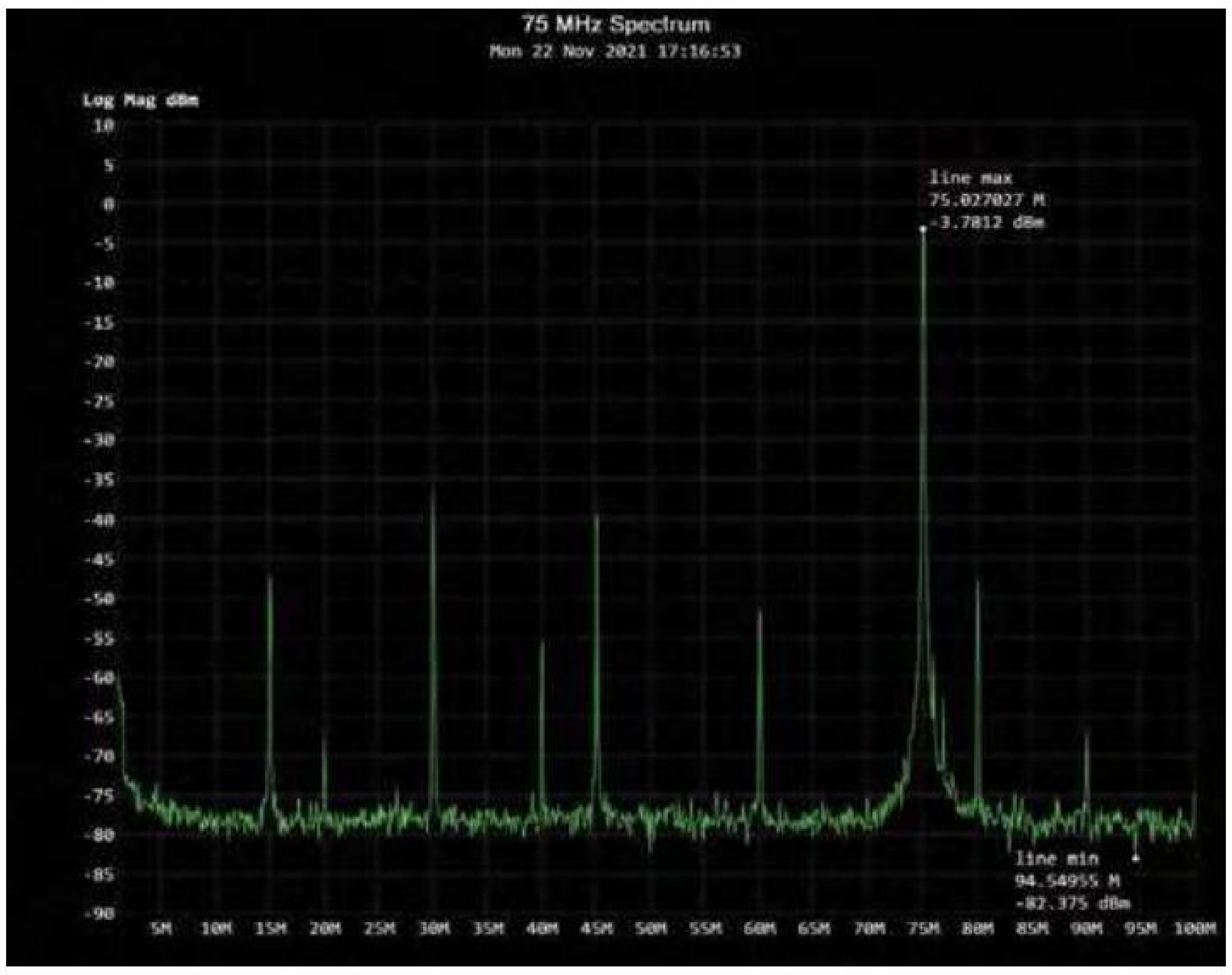


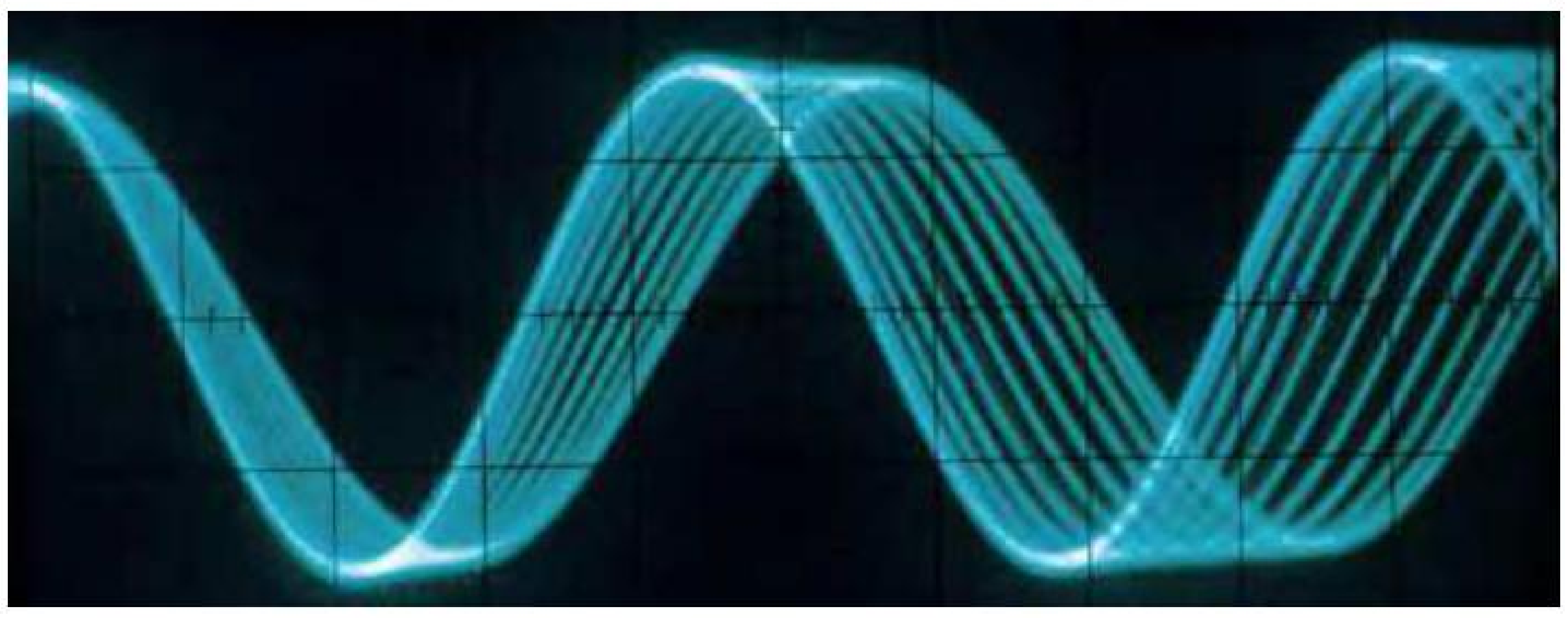
A 300kHz signal with 10kHz amplitude modulation applied, resulting in smaller peaks 10kHz on either side of the carrier wave.



Here frequency modulation has been applied. This results in many small peaks of all sorts of multiples of modulating waves either side of the carrier wave, but this spectrum analyser doesn't have the resolution to separate them.



Spectral analysis of a 75MHz output signal. Because of how a DDS works, you not only get spurious peaks at multiples of the signal frequency but also at fractions. The most significant in this case is at 30MHz, 35dB below the fundamental.



A 100kHz output signal modulated by 1kHz at 10kHz deviation. This doesn't show on my digital scope, but my old analogue scope provides this pattern.

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- Up to 32 Mpts memory per channel
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CH1
80V
CH2
AWG

Handyscope HS5

The 500 MSa/s 14 bit dual channel High Resolution Oscilloscope with function generator.

CH1
80V
CH2
80V
CH3
80V
CH4

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- Up to 100 MSa/s continuous streaming
- Up to 256 Mpoints memory per channel
- 0.25 % DC vertical accuracy, 0.1 % typical
- 1 ppm time base accuracy

CH1
CH2
CH3
CH4
5-15VDC
CMI 1
CMI 2

Automotive Test Scope
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Model	Configuration				Order Code	Price £
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Handyscope HS5-055-W5				*Extended Warranty*	HS5-055-W5	£ 945.00
Handyscope HS5-055S		*SureConnect*			HS5-055S	£ 957.00
Handyscope HS5-055S-W5		*SureConnect*		*Extended Warranty*	HS5-055S-W5	£1,007.00
Handyscope HS5-055XM	*eXtended Memory*				HS5-055XM	£ 930.00
Handyscope HS5-055XM-W5	*eXtended Memory*			*Extended Warranty*	HS5-055XM-W5	£ 981.00
Handyscope HS5-055XMS	*eXtended Memory*	*SureConnect*			HS5-055XMS	£ 993.00
Handyscope HS5-055XMS-W5	*eXtended Memory*	*SureConnect*		*Extended Warranty*	HS5-055XMS-W5	£1,043.00
Handyscope HS5-110				*100 MSa/s base model*	HS5-110	£ 984.00
Handyscope HS5-110-W5				*Extended Warranty*	HS5-110-W5	£1,034.00
Handyscope HS5-110S		*SureConnect*			HS5-110S	£1,046.00
Handyscope HS5-110S-W5		*SureConnect*		*Extended Warranty*	HS5-110S-W5	£1,096.00
Handyscope HS5-110XM	*eXtended Memory*				HS5-110XM	£1,020.00
Handyscope HS5-110XM-W5	*eXtended Memory*			*Extended Warranty*	HS5-110XM-W5	£1,070.00
Handyscope HS5-110XMS	*eXtended Memory*	*SureConnect*			HS5-110XMS	£1,082.00
Handyscope HS5-110XMS-W5	*eXtended Memory*	*SureConnect*		*Extended Warranty*	HS5-110XMS-W5	£1,132.00

WiFiScope WS6 DIFF

Model	Configuration				Order Code	Price £
WiFiScope WS6 DIFF-200				*200 MSa/s base model*	WS6-DIFF-200	£1,581.00
WiFiScope WS6 DIFF-200-W5				*Extended Warranty*	WS6-DIFF-200-W5	£1,661.00
WiFiScope WS6 DIFF-200G			*SafeGround*		WS6-DIFF-200G	£1,686.00
WiFiScope WS6 DIFF-200G-W5			*SafeGround*	*Extended Warranty*	WS6-DIFF-200G-W5	£1,766.00
WiFiScope WS6 DIFF-200S		*SureConnect*			WS6-DIFF-200S	£1,672.00
WiFiScope WS6 DIFF-200S-W5		*SureConnect*		*Extended Warranty*	WS6-DIFF-200S-W5	£1,752.00
WiFiScope WS6 DIFF-200SG		*SureConnect*	*SafeGround*		WS6-DIFF-200SG	£1,778.00
WiFiScope WS6 DIFF-200SG-W5		*SureConnect*	*SafeGround*	*Extended Warranty*	WS6-DIFF-200SG-W5	£1,858.00
WiFiScope WS6 DIFF-200XM	*eXtended Memory*				WS6-DIFF-200XM	£1,627.00
WiFiScope WS6 DIFF-200XM-W5	*eXtended Memory*			*Extended Warranty*	WS6-DIFF-200XM-W5	£1,707.00
WiFiScope WS6 DIFF-200XMG	*eXtended Memory*		*SafeGround*		WS6-DIFF-200XMG	£1,732.00
WiFiScope WS6 DIFF-200XMG-W5	*eXtended Memory*		*SafeGround*	*Extended Warranty*	WS6-DIFF-200XMG-W5	£1,812.00
WiFiScope WS6 DIFF-200XMS	*eXtended Memory*	*SureConnect*			WS6-DIFF-200XMS	£1,718.00
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WiFiScope WS6 DIFF-200XMSG	*eXtended Memory*	*SureConnect*	*SafeGround*		WS6-DIFF-200XMSG	£1,824.00
WiFiScope WS6 DIFF-200XMSG-W5	*eXtended Memory*	*SureConnect*	*SafeGround*	*Extended Warranty*	WS6-DIFF-200XMSG-W5	£1,904.00

Automotive

Model	Configuration	Order Code	Price £
Automotive Diagnostic Kit ADK610004DW	*With ATS610004DW-XMSG*	TP-ADK610004DW	£2,524.00
Automotive Diagnostic Kit ADK610004DW Lite	*With ATS610004DW-XMSG + ATIS Lite*	TP-ADK610004DW-Lite	£2,682.00
Automotive Diagnostic Kit ADK610004DW Pro	*With ATS610004DW-XMSG + ATIS Pro*	TP-ADK610004DW-Pro	£2,928.00
Automotive Diagnostic Kit ADK605004DW	*With ATS605004DW-XMS*	TP- ADK605004DW	£2,195.00
Automotive Diagnostic Kit ADK605004DW Lite	*With ATS605004DW-XMS + ATIS Lite*	TP-ADK605004DW-Lite	£2,352.00
Automotive Diagnostic Kit ADK605004DW Pro	*With ATS605004DW-XMS + ATIS Pro*	TP-ADK605004DW-Pro	£2,598.00
Automotive Diagnostic Kit ADK5004DW	*With ATS5004DW*	TP- ADK5004DW	£1,957.00
Automotive Diagnostic Kit ADK5004DW Lite	*With ATS5004DW + ATIS Lite*	TP- ADK5004DW-Lite	£2,115.00
Automotive Diagnostic Kit ADK5004DW Pro	*With ATS5004DW + ATIS Pro*	TP-ADK5004DW-Pro	£2,361.00
Automotive Diagnostic Kit ADK610004D	*With ATS610004D-XMSG*	TP-ADK610004D	£2,258.00
Automotive Diagnostic Kit ADK610004D Lite	*With ATS610004D-XMSG + ATIS Lite*	TP-ADK610004D-Lite	£2,415.00
Automotive Diagnostic Kit ADK610004D Pro	*With ATS610004D-XMSG + ATIS Pro*	TP-ADK610004D-Pro	£2,661.00
Automotive Test Scope ATS610004D-XMSG	*USB*	ATS610004D-XMSG	£1,798.00
Automotive Test Scope ATS605004D-XMS	*USB*	ATS605004D-XMS	£1,469.00
Automotive Test Scope ATS5004D	*USB*	ATS5004D	£1,549.00

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Vifa 19mm BC20SC15-04 tweeter (each)	**£15**
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Volt crossover inductors

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Note '10/63' denotes '10µF 63V'.

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Mullard 'Mustard' C296 0.22/400	**£2.00**

Polycarbonate

Axial 2.2/63 1%, 4.7/160, 6.8/63	**£1.00**

Radial

6.8/160V, 10/63	**£2.00**
Reclaimed 22/63	**£2.00**

Polystyrene

Philips 1% 4.7nF/160, 6.2nF/500, 12nF/63, 22nF/63, 110nF/63	**£1.00**
RIFA 1% 100nF/100	**£2.00**
Suflex 2.5% 10nF/63 (rad. or ax.)	**£0.50**

Radiation resistant

Siemens cellulose acetate MKL 2.2/25	**£0.80**

Electrolytic – Mullard blue 017 series

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150/40, 470/40,1000/40	**£1.00**

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4.7/50, 6.8/35, 10/25, 10/35, 22/15	**£1.00**

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680/6.3	**£3.00**

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Castanet button 140/30, 470/3	**£3.20**
Hughes 540/10	**£3.20**

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100/35	**£4.00**

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Special resistors

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Thermistor CZ1, CZ6	**£1.50**
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Lots of big valve resistors available.

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Miscellaneous

Theremin Clearance Sale!

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PCBs

Pocket Theremin (*EPE*, 1996)	**£4.00**
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Switches Blore Edwards/Plessey

MH1 4-pole 3-way	**£3.00**
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Contact

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Our SMD Test Tweezers project from the October 2022 issue has been extremely popular. This did not come as a surprise given that they are handy, compact, easy to use, easy to build and the cost is reasonable. We decided to see what features we could add simply by upgrading the microcontroller at its heart.

SILICON CHIP
SMD TEST TWEEZERS
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CON+
SILICON CHIP SMD TEST TWEEZER ARM 04106212 ©2021

Improved SMD Test Tweezers

The 2022 SMD Tweezers are a simple but clever design. A PIC12F1572 eight-pin microcontroller powered from a button cell is used to probe resistors, diodes and capacitors and then display its findings on a tiny OLED screen.

The PIC12F1572 does a respectable job, but the *Test Tweezers* software takes up all but 42 bits of the available Flash memory, leaving no room for expansion.

We used the PIC12F1572 for the 2022 *SMD Test Tweezers* as it was the cheapest available at the time, apart from its close relative with less memory, the PIC12F1571. Until recently, the PIC12F675 and later PIC12F617 were our 8-pin micros of choice, but Microchip keeps bringing out new parts with better performance and more features at lower prices, so we try to keep up.

The PIC12F1572 is more capable than the older PIC12F675. However, when we looked into upgrading the *Test Tweezers* with some software improvements, we realised that the PIC12F1572 did not have enough free memory to add new features or improve the existing ones. For that, we would have to move to the latest generation of PICs.

So when a new family of PICs became available, we began to investigate what we could add by using them.

A new PIC

The original (2022) *SMD Test Tweezers* don't use any exotic peripherals within the micro; the analogue-to-digital converter (ADC) and watchdog timer that the software requires are found in most PIC microcontrollers. The low-power sleep mode is quite standard too, and is essential for standby operation when powered from a cell. This allows the Tweezers to be left idle but ready to work at a second's notice.

The I^{2}C interface to the OLED display is emulated in software by toggling GPIO (general purpose input/output) pins, a technique often known as 'bitbanging'. This all means that just about any 8-pin microcontroller with more program memory could be used for the *SMD Test Tweezers*.

After developing the original *SMD Test Tweezers*, we became aware of the PIC16F152xx series of microcontrollers. The range spans parts from eight to 40 pins. While the range has features that are modest by current standards, they are still more capable than older devices such as the PIC12F675.

The PIC16F15213 and PIC16F15214 are the 8-pin parts in the range, and they are cheaper than the PIC12F1572, although the current part shortages mean that availability is patchy. (For example, Mouser expects to have stock of the PIC16F15214-I/SN by 1 May 2023, which is annoying, but not the terrible 12-month lead times we endured at the height of the pandemic!)

Caution

Like any project that uses coin cells, the Tweezers should be kept well away from children who may ingest them. The Tweezers also have quite pointy tips, another reason to keep them out of reach of young fingers.

Importantly, the PIC16F15214 is available in the SOIC package and has twice the Flash memory of the PIC12F1572. Microchip does a pretty good job of maintaining pin compatibility between parts, and the PIC16F152xx series is no exception.

The upshot is that the PIC16F15214 is both cheaper and fully capable of replacing the PIC12F1572 as the controller for the *SMD Test Tweezers*, while also having the larger program space needed for us to add new features.

Tweezers 2.0

We have implemented three major updates to the *SMD Test Tweezers*.

First, we expanded the capacitance measurement range in both directions (it can measure both larger and smaller capacitances than before).

Second, we added a calibration and setup procedure.

Finally, we improved usability for left-handed people (or those who want to hold something like a soldering iron in their right hand) by allowing the screen display to be rotated by 180°.

These improvements have all been made in software, so apart from changing the PIC12F1572 to the PIC16F15214, the hardware is identical and the general operation is much the same.

By Tim Blythman

Features and specifications

- Uses identical hardware to the original Tweezers (PE, October 2022) apart from the PIC microcontroller
- Identifies component type (resistor, capacitor, diode or LED) and measures critical values
- Resistors: value from 10Ω to 1MΩ
- Diodes: forward voltage up to about 3V
- Capacitors: value from (approximately) 10pF to 150µF
- Cell voltage with nothing connected
- Low power sleep when idle avoids the need for an on/off switch
- Instant wake-up by touching probe tips together
- Option to select left-handed or right-handed display
- Calibration of internal and contact resistance

Circuit details

Fig.1 shows the circuit, which is the same as last time (*PE*, October 2022), besides IC1. All the readings are displayed on a tiny OLED module connected to CON2.

IC1 drives its RA5 (pin 2, IOTOP) and RA4 (pin 3, IOBOT) pins high and low and measures the voltage present on pin 5 with its ADC peripheral. For example, it can determine the resistance of a resistor connected between the CON+ and CON– points using the voltage divider equation.

Diodes will present their forward and reverse voltages between CON+ and CON– when the micro applies a voltage. The micro determines the diode's orientation, showing its polarity and forward voltage.

Capacitors are first charged by bringing IOTOP high and IOBOT low and then characterised by measuring the rate of discharge when IOTOP is brought low. The Tweezers can even measure their own supply voltage by reading the voltage of its internal 1.024V reference relative to that supply voltage.

These features are already present in the original *SMD Test Tweezers*, so we suggest you refer to the original October 2022 article for more detail on how these features work and how the values are calculated.

Improvements

The upper limit of the capacitance range was limited by the use of an 8-bit counter to time the discharge. With more Flash memory and RAM available, we can instead use a 16-bit counter.

In theory, this expands the range by a factor of 256, but in practice, using this entire range is not possible. The upper limit is around 150µF now, equivalent to about 12 bits or a factor of 16 higher.

The first reason for this is that higher values would overflow the 32-bit mathematical calculations that are required. The second is that the time needed to charge and discharge a larger capacitor becomes unreasonably long, in the order of several seconds between readings.

The only way to overcome this would be to change the series test resistor, which would affect the other readings too.

The relatively high value of the series test resistor also means that capacitance readings can be distorted by leakage current. Since leakage is typically higher in higher-value parts, especially in electrolytic capacitors, the accuracy and usefulness of these higher ranges are less than what seems theoretically possible.

So higher-value capacitors can be measured and will return a reading, possibly after a brief delay, but the accuracy will not be as good as for lower values.

Low-capacitance measurements

Values lower than 1nF are measured in an entirely different fashion. This method is so sensitive that it can measure the capacitance of the touch of a hand, in the order of picofarads.

It's called shared capacitance sensing, and we used it to detect finger touches in the *ATtiny816 Breakout Board* of July 2021.

It works by comparing the relative magnitude of two capacitors by initially charging one and discharging the other, as shown in Fig.2. When they are connected, the charge present is shared between the two in proportion to their capacitances.

The ratio of the initial and final voltages relates directly to the ratio of the capacitances. The theory and mathematics are explained further in the *ATtiny816 Breakout Board* article.

In the case of our new *SMD Test Tweezers*, a capacitor connected to CON+ and CON– is charged up via the 10kΩ resistor. The second capacitor is actually the tiny internal capacitor that is used to sample and hold the voltages read by the microcontroller's ADC.

This capacitor is nominally 5pF, and it is discharged by sampling an ADC channel connected to ground.

Fortunately, the ADC peripheral has a selection to make an internal ground connection, so this doesn't need an extra pin. The external capacitor is disconnected from its resistor, and the two capacitors are connected by taking an ADC reading from the external capacitor.

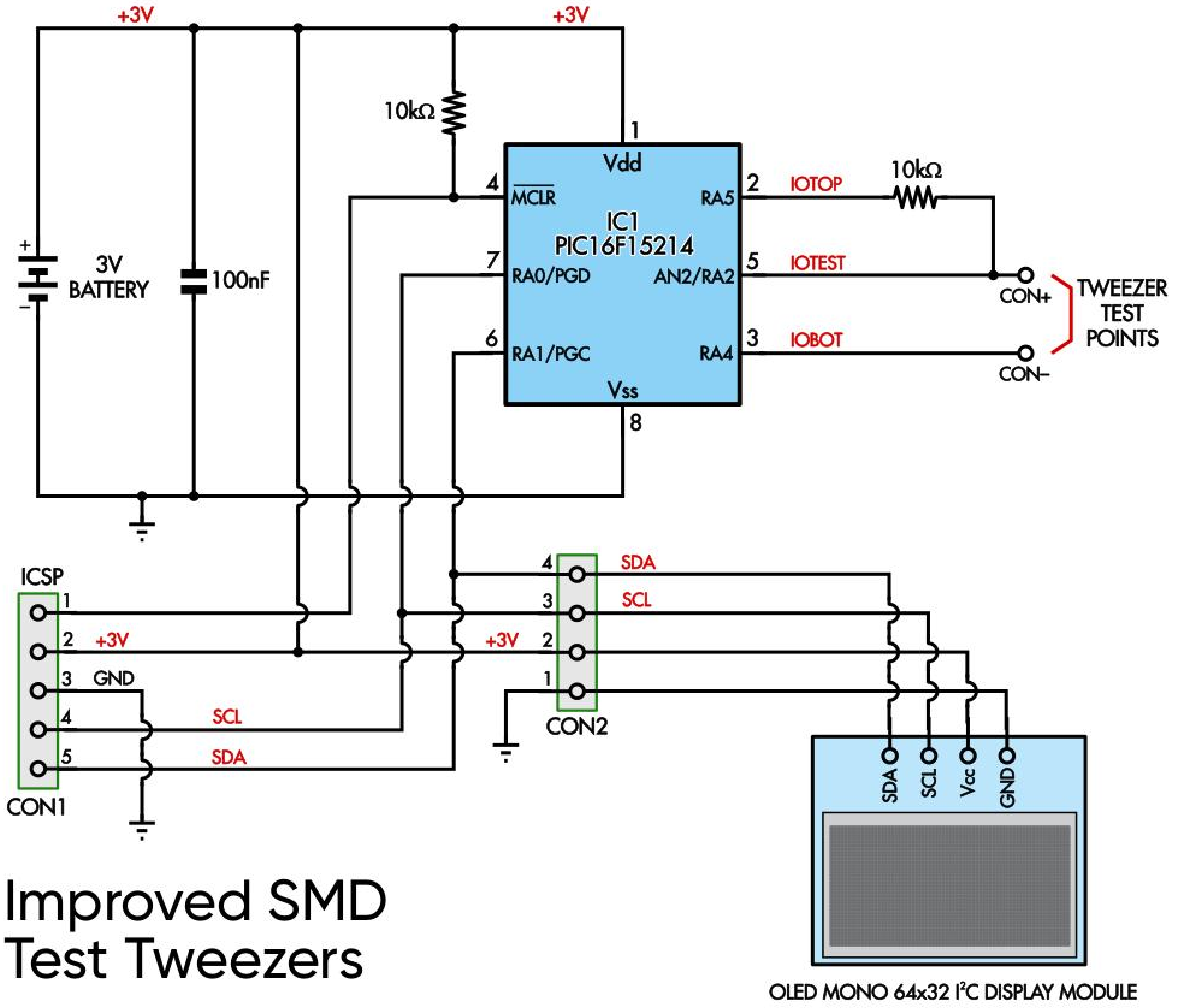
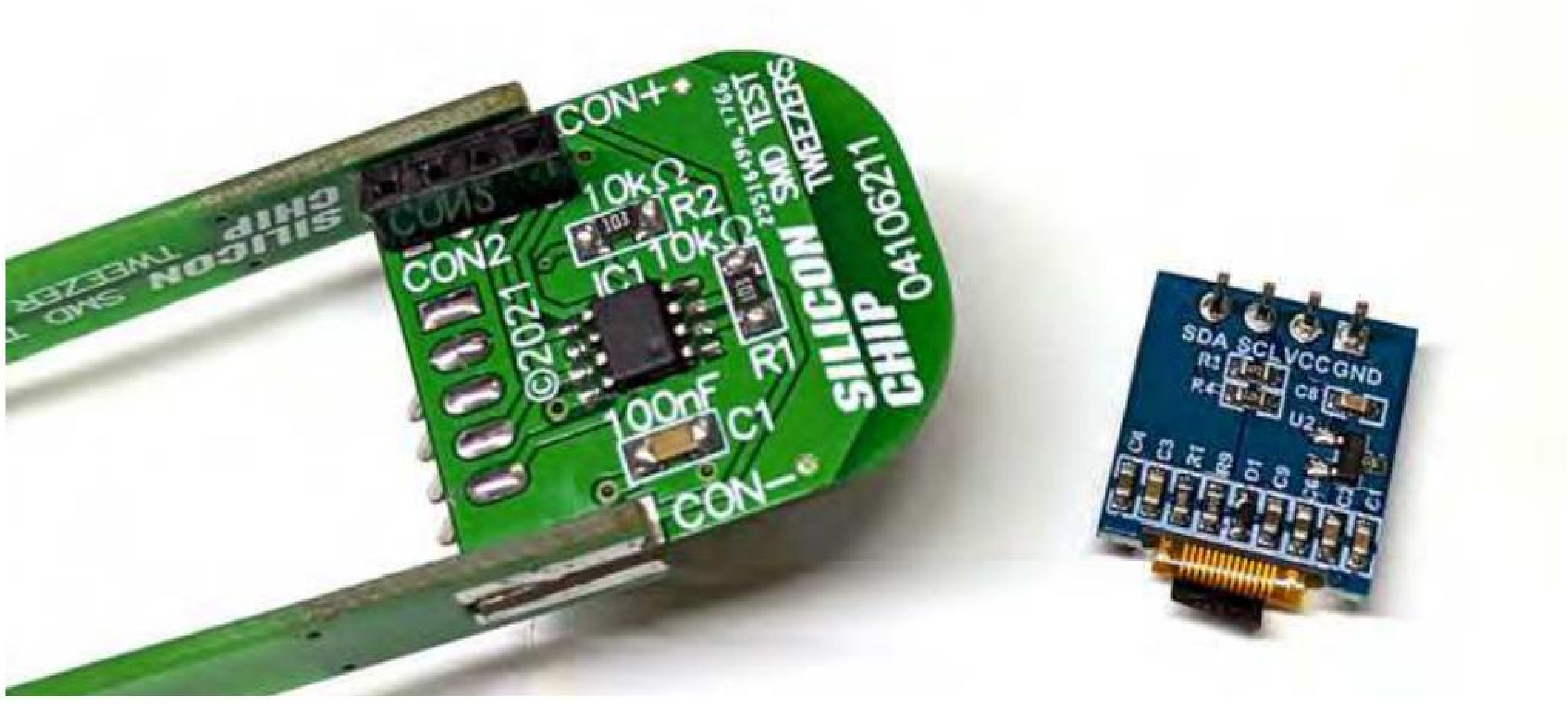


Fig.1: the circuit for the updated Tweezers is practically the same as the old version, except IC1 is now a PIC16F15214. It can perform all its tests by applying different voltages to the IOTOP and IOBOT pins and testing the voltage on the IOTEST pin.

A few constructors had difficulty finding the brass strips we recommended for the original Tweezers. Standard header pins are a substitute and are easily aligned for soldering while in their plastic shrouds. There are even gold-plated versions available.



We used a low-profile header socket (Altronics P5398) so that we could remove the OLED module during prototyping, to allow access to the programming pins. This also required us to cut down the header pins on the underside of the OLED and remove the plastic spacer block. The alternative is to simply solder the OLED directly to the main PCB.

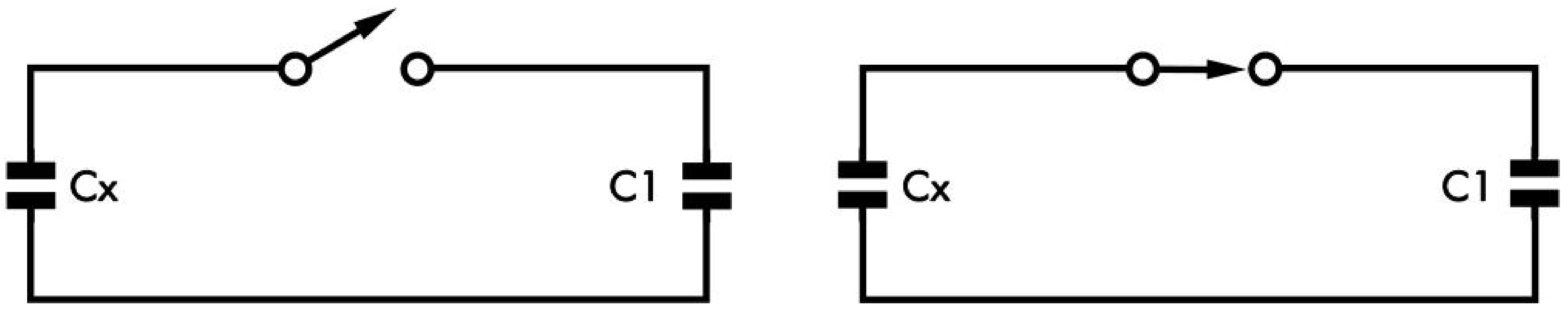
An equation similar to the voltage divider equation is used on the ADC result to calculate the value of the external capacitor. The way the capacitors share the charge is analogous to how resistors share voltage in a divider chain.

The software also makes minor adjustments to account for some of the stray capacitance that is present and significant at these magnitudes. We made tests on real capacitors in the picofarad range to fine-tune these readings.

The lower limit is fairly arbitrary and is chosen to avoid the *SMD Test Tweezers* detecting stray capacitance as a component to be measured, which could cause them not to power down correctly. At these scales, even the way the *Tweezers* are held can change the reading substantially.

As the ADC reading nears its upper limit for larger capacitances, the resolution is poor around 1nF, and steps grow to be as far as 100pF apart. So the readings using this method are always shown as pF, and other methods are used for measurements in nF or µF.

We will detail the calibration and setup process after the construction is complete.



$$V_{across\,Cx} = V_{initial},\ C = Cx$$
$$\Rightarrow Q_{across\,Cx} = V_{initial} \times Cx$$
$$V_{across\,C1} = 0,\ C = C1$$
$$\Rightarrow Q_{across\,C1} = 0 \text{ (because } V_{across\,C1} = 0\text{)}$$

$$C = Cx + C1 \text{ (parallel capacitors)}$$
$$Q = Q_{across\,Cx} + Q_{across\,C1} = V_{initial} \times Cx$$
(conservation of charge)

measure V_{final}
$$\Rightarrow Cx = (V_{final} \times C1) \div (V_{initial} - V_{final})$$

Fig.2: Cx is the device under test (DUT) connected to the Tweezer probes, while C1 is the ADC sample-and-hold capacitor inside the microcontroller. The capacitors are connected by sampling Cx with the ADC. If the value of Cx equals C1, the resulting voltage is half the initial voltage. It's analogous to a resistive voltage divider, and the formulas are much the same, with the capacitor charge replacing the voltage across the resistors.

Construction

The assembly procedure is identical to the October 2022 design, but we'll go over it again for those who haven't seen that article. The *SMD Test Tweezers* are built using three PCBs, with the main one coded 04106211, measuring 28 x 26mm and available from the *PE PCB Service*. Refer to the PCB overlay diagrams, Fig.3 and Fig.4, during construction.

The main PCB is not hard to build, even if the parts are all surface-mounting types. Gather your SMD tools and supplies. We recommend a fine-tipped soldering iron, a magnifier, some flux paste, solder wicking braid and tweezers, at a minimum.

The small PCB needs something to hold it in place. If you don't have an appropriate vice tool, you can use an adhesive putty like Blu-Tack instead.

If possible, set up some fume extraction to deal with the extra smoke that comes from working with flux, or work near an open window or outside. A tip-cleaning sponge is handy too.

Apply flux to the top PCB pads for IC1 and the three passive components, then rest IC1 in place using tweezers, ensuring the pin 1 dot or bevel is towards the curved end of the board. Align the part within the pads, clean the iron's tip, apply fresh solder and tack one lead in place.

Adjust the IC if necessary to ensure it is flat against the PCB and aligned to the pads. Then solder the remaining pins, cleaning your iron's tip and adding solder as necessary.

Use the braid to remove any solder bridges by adding more flux, then press the braid against the excess solder with the iron. Carefully drag both iron and braid away when the solder has been absorbed.

The remaining three components are not polarised, so their orientations are unimportant. The capacitor sits near CON−, while the two identical resistors flank IC1 at its other end and side.

Use a similar technique to IC1. Tack one lead, adjust the part, then tack the other lead. You can also go back and refresh any leads if the joint doesn't look right. It should be smooth and glossy; you can add more flux at any stage to help improve solderability.

Then solder the single component to the back of the PCB. Centre the cell holder to align the two external pins to their pads. If your iron is adjustable, turn it up while soldering this larger part. You should also ensure that the wider opening on the cell holder faces the rounded edge of the PCB to allow access for the cell to be fitted and removed.

As before, apply flux, tack one lead in place and adjust the position. Then solder the other lead. For these much larger pads, it can help to apply extra solder directly to the pad to create a robust fillet, which you can see in our photos.

With the surface mounted parts fitted, you can clean up the PCB using the flux cleaner designated by the flux's data sheet. Methylated spirits or

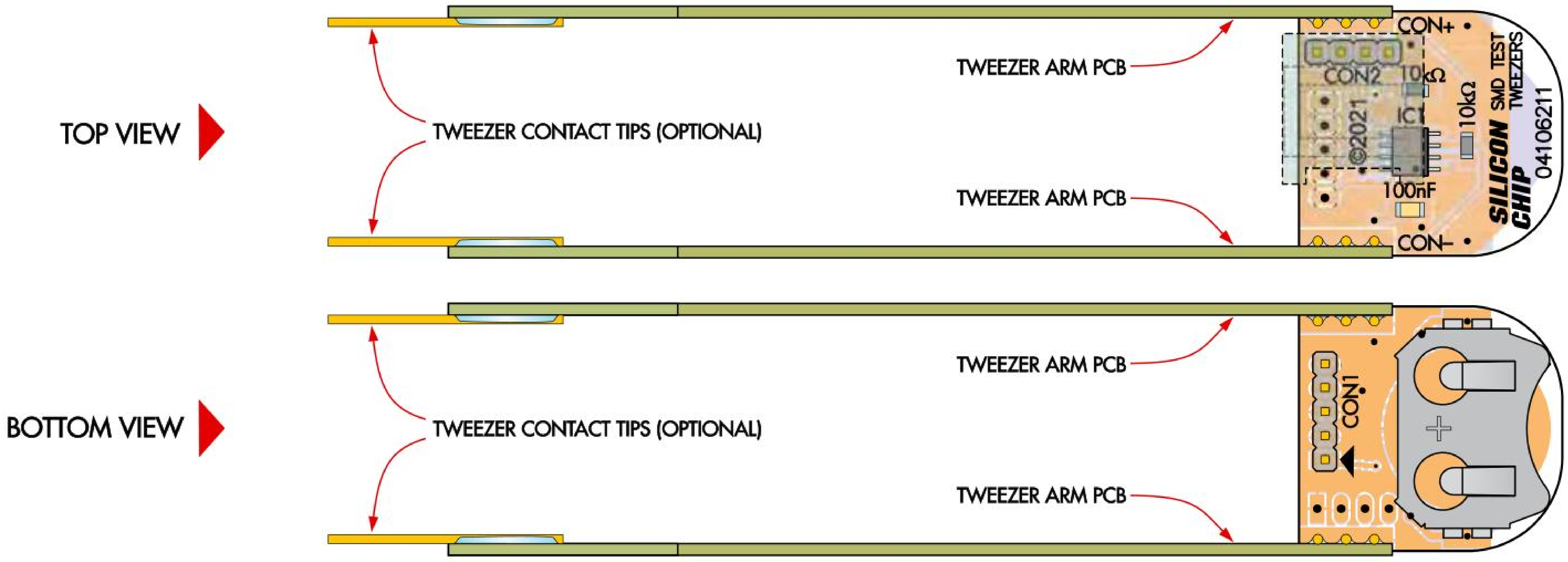


Fig.3: construction of the Tweezers is the same as last time (October 2022) except that IC1 is a different, pin-compatible microcontroller with more memory. There aren't many components to fit but make sure that IC1 is oriented correctly.

isopropyl alcohol are good all-round alternatives for cleaning many fluxes too, while general-purpose flux cleaners are also available (and generally work better than plain alcohol).

Just ensure that any flammable solvent has fully evaporated before moving on to the next steps.

Programming IC1

You have two options for loading IC1's firmware. First, you can buy a preprogrammed PIC from the *PE PCB Service*; or, you can buy and program a PIC yourself. (Skip the following if your microcontroller has been preprogrammed.)

As we noted in the panel, the PIC16F15214 is a much newer part than the PIC12F1572, so you will need a fairly new programmer and a new version of Microchip's MPLAB X IPE (integrated programming environment). It can be downloaded as part of the MPLAB X IDE from: **https://bit.ly/pe-may23-ide**

We've tested with versions v5.40 and later. You may also need to download a DFP (device family pack); this can be downloaded from within the IDE, and the IPE then detects that the DFP is installed. You should look for the PIC16F152xx family.

You will also need a recent programmer such as a Snap or PICkit 4 as the older PICkit 3 is not supported for these parts.

Connect the programmer to the PCB at CON1, aligning the arrows that mark pin 1. You could solder on a header, but we find that holding a short header strip in place and pressing it firmly against the pads to make contact is usually sufficient.

Select the PIC16F15214 part and open the **0410621B.HEX** file, which is available for download from the May 2023 page of the *PE* website: **https://bit.ly/pe-downloads**

You may need to change the settings to allow the programmer to apply power. Then click 'Program' and check that the part programs and verifies correctly.

Tweezer arms

The two arm PCBs should be attached next, as the OLED module covers much of the main PCB, limiting access.

Our first version of the *SMD Test Tweezers* used small pieces of brass strip to give the arms finer tips than just the bare PCBs would provide. If you can't find a brass strip, then we suggest an alternative that will provide your Tweezers with gold-plated tips!

Many header pins are gold-plated and are a good size for working with small components. These can be used instead of the brass strip, but unlike the brass strip, we found it easier to solder these to the arms after attaching the arms to the main PCB.

The other advantage of using the header pins is that they are a good fit for breadboards and jumper wires, making it very easy to connect the *SMD Test Tweezers* to other components for hands-free readings.

We recommend fitting the arms roughly in line with the edges of the PCB but slightly tilted inwards with around 15mm separation at the tip ends. Like the SMD parts, roughly tack the arms in place and adjust them to your liking.

We prefer fitting the arms with the writing and main contact trace running down the inside. This helps shield and isolate the trace from outside contact or stray capacitance.

Test the action/pressure of the *Tweezers* when the arms are positioned. When you are happy, apply a generous amount of solder on both sides of the main PCB to secure them firmly in place.

Parts List – Improved SMD Test Tweezers

1 double-sided PCB coded 04106211, 28 x 26mm (main PCB)*
2 double-sided PCBs coded 04106212, 100 x 8mm (Tweezer arms)*
1 PIC16F15214-I/SN or PIC16F15214-E/SN 8-bit microcontroller programmed with 0410621B.HEX, SOIC-8 (IC1) •*
1 0.49-inch 64x32 I^2C OLED module [eBay, AliExpress – for example, at the time of writing eBay item 154706482381]
1 surface-mount coin cell holder (BAT1) **[Digi-key BAT-HLD-001-ND, Mouser 712-BAT-HLD-001 or similar]**
1 CR2032 or CR2025 lithium coin cell
1 5-pin right-angle male pin header (CON1; **optional**, for programming IC1 in-circuit)
1 100nF SMD 50V X7R ceramic capacitor, 3216/M1206 size **[Altronics R9935]**
2 10kΩ 1% SMD resistors, 3216/M1206 size **[Altronics R8188]**
2 15 x 2mm short pieces of thin (eg, 1mm) brass sheet for tips (**optional**)
OR
2 gold-plated header pins for tips (see text) •
1 40mm length of 30mm diameter clear heatshrink tubing (**optional**)
2 100mm lengths of 10mm diameter heatshrink tubing (**optional**)
1 4-way low-profile female header strip (**optional**, for CON2; can be cut from Altronics P5398) •

• *These parts have been changed compared to the original Tweezers*
* *Available from the PE PCB Service*

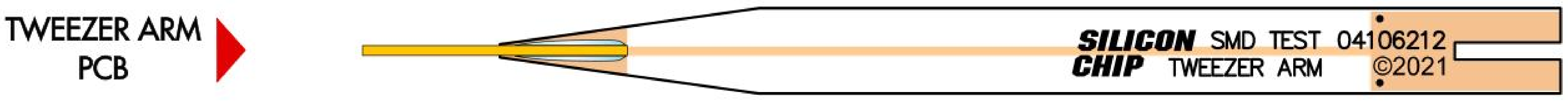


Fig.4: the PCB for the Tweezer Arm section.

To fit the tips, find a strip of about six pin headers (to maintain the 15mm separation) and while the pins are still in the plastic holder, solder the tips of the arms to the short ends of the headers. Using the holder will keep the pins parallel and even.

Again, apply a generous amount of solder when you are happy with the tips, then carefully and evenly pull the arms and their tips out of the plastic holder. We find that some pointy-nosed pliers are handy to help in this situation.

OLED screen

The final step is to fit the OLED display module. You can solder the module directly to the main PCB. But since we had to do a lot more testing for this new version, we used a low profile header socket to allow the OLED to be removed. This is necessary because the programming pins are also used to interface with the OLED screen.

We used the *PIC Programming Helper* from June 2022 to help with our testing. But we also needed to do some testing and tweaking on the final design, so having a removable display was handy for these later stages. We used a low-profile (5mm high) header socket to keep the unit compact, and it's what you can see in our photos.

But we recommend using the direct mounting method unless you are considering designing your own firmware. So we'll describe that.

If the OLED module's header is not attached, solder it now, at right angles to the module's PCB. Then mount the module onto the PCB. You might find that the back of the OLED module touches IC1. In this case, use Blu-Tack or a cardboard shim to keep the two apart until the module is securely soldered.

That leaves the long pins protruding at the back of the PCB. You can trim them carefully with a sharp pair of sidecutters.

Testing

Fit a CR2025 or CR2032 3V coin cell into the cell holder, noting the polarity on the cell holder. After about a second, the OLED should show R HAND as per Screen 1. If not, check your soldering and that 3V is present on either the OLED module's header pins or pins 2 and 3 of CON1.

If 3V is not present, the cell may be flat or there is a short circuit. Remember to check the reverse of the PCB, as the cell holder, arms and OLED header are all very close together.

Before you proceed to use the *SMD Test Tweezers*, you might like to go through the calibration procedure, as detailed in the panel overleaf.

Operation

With the calibration and setup complete, normal operation will start. You should see a display indicating the battery voltage preceded by the letter B. After five seconds, the *Tweezers* will enter sleep mode and can be woken by touching the tips together.

At this point, the new *SMD Test Tweezers* work much the same as the older version, apart from the expanded capacitance range.

If you close the tips to measure the *Tweezers'* short-circuit resistance, you should see a value jumping around between 0Ω and 1Ω if everything is working correctly.

We measured the current consumption on our prototype as much the same as the original *SMD Test Tweezers*. The new *Tweezers* use around 4mA when working and 5µA when sleeping. So the cell life will depend mainly on how much they are used, tending towards the cell's shelf life.

Finishing touches

Like we did with the original *SMD Test Tweezers*, you might also consider adding some heatshrink to the device to add some protection and to keep the battery from being removed.

The 10mm heatshrink can be put over the arms, leaving just the tips exposed. It should be pushed up firmly against the main PCB before being shrunk with a heat gun.

The wider heatshrink fits over the main PCB and should overhang the end enough to prevent the cell from being removed. Of course, you will have to remove and replace the heatshrink to replace the cell.

Also, be careful to not shrink the large heatshrink too tightly around the OLED, as its glass screen can be fragile. Aim heat along the edges to avoid heating the OLED and battery, and only shrink enough to secure everything in place.

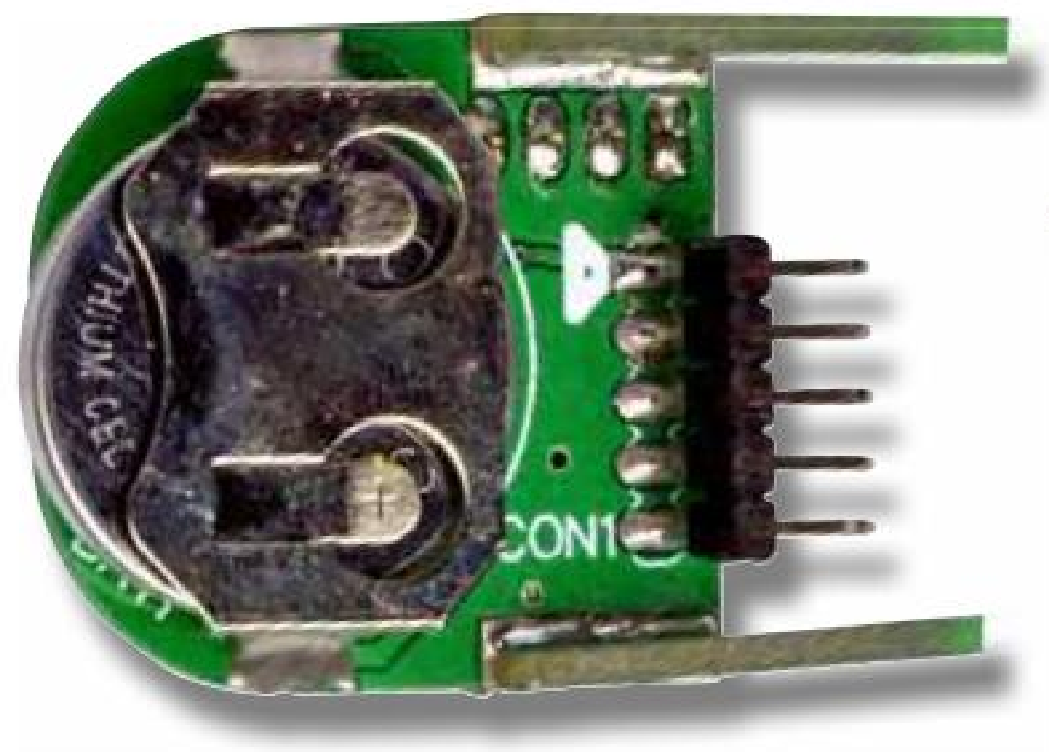
Parts availability and upgrading

Apart from the PIC, the *hardware* is the same as before. The PCBs can be bought from the October 2022 section of the *PE PCB Service*, and the new version PIC from the May 2023 page.

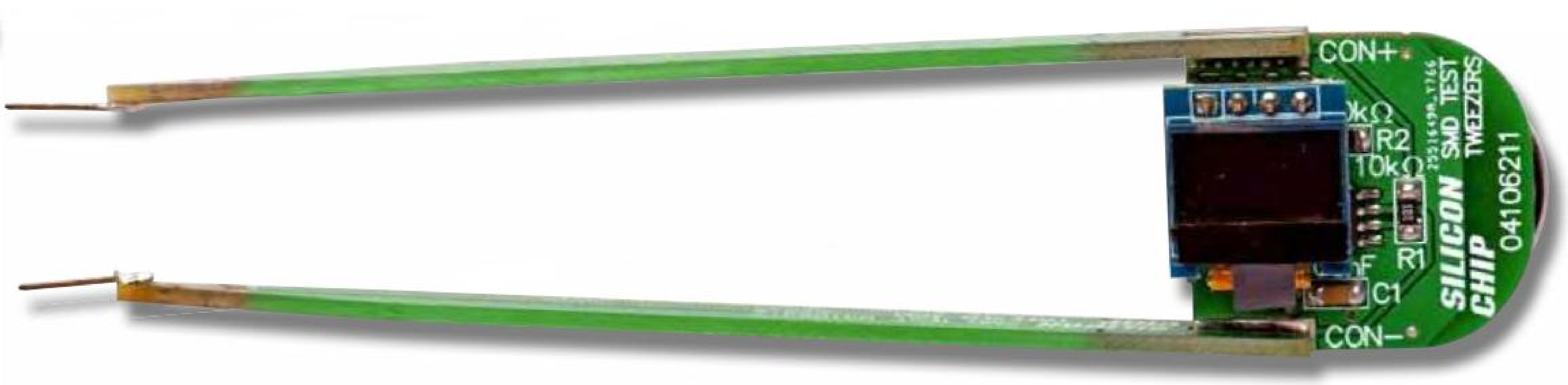
While we think the parts cost is low enough that it's worthwhile simply building new Tweezers, if you really want to upgrade a pair you've already built, you can just order the programmed micro from us and swap it over.

We suggest you only do this if you are confident in removing SMDs and

Screen 1: the first display when the Tweezers are powered on is the HAND setting, oriented in correspondence to the setting. Leaving the tips open selects right-handed operation.



It helps to apply extra solder directly to the pad of the Tweezer arms to make a robust fillet.



The tips might look a bit wonky, but when the arms are squeezed to bring them together they become parallel at about the distance you would typically use them (wide enough to hold a typical SMD component).

cleaning up the board to accept a new chip. This is most easily done with a hot air station, although it can be done with a regular soldering iron if you know how.

Future improvements

The *SMD Test Tweezers* are somewhat limited by only having one resistor to apply voltages to components, which is in turn limited by the 8-pin PIC. The 10kΩ resistor limits the applied current to about 300µA, meaning that the diode forward voltages reported are much lower than expected, and LEDs do not light very brightly.

SETUP AND CALIBRATION

The accuracy of modern surface-mounted resistors is excellent and, as built, the *SMD Test Tweezers* will distinguish resistors well enough for most constructors. Still, the extra program space available on the PIC16F15214 gives us room to add some routines to add some settings and calibration constants.

I'm right-handed, and have realised I overlooked an aspect of the design that probably makes the original *Tweezers* very difficult to use for the left-handed. So the first new setting is the option to flip the display so that it is legible when the *SMD Test Tweezers* are held in a left hand.

There is also the option to set the value of the nominally 10kΩ series resistor between pins 2 and 5 of IC1. Rather than trying to measure its value, we recommend testing an external part of a known value and adjusting the calibration until the *SMD Test Tweezers* measure it correctly.

The series value is simply adjusted in proportion to the desired change in calculated resistance. For example, if your displayed test resistor is 1% low, increase the series resistor value by 1%.

This won't adjust for things like trace and contact resistance, so there is a separate calibration step for those. Still, the preset value we have loaded into the *SMD Test Tweezers* firmware will be quite accurate, as long as your build is similar to ours.

You may have noticed that the *SMD Test Tweezers* do not have any buttons. So the various settings are configured using the only input device available: the probe tips!

We can step through the setup and calibration by opening and closing the tips of the Tweezers at various points. It's a slow but effective process, made easier by having a screen to show what is happening.

Look at the flowchart in Fig.5 as we explain the process. The setup procedure only runs when the microcontroller is powered up, so it can be triggered by removing and reinserting the cell.

The right-hand or left-hand operation setting is selected at the instant power is applied. If the tips are open, right-handed operation is selected; otherwise, left-handed operation is set. A message is also shown to RELEASE (Screen 2) the tips, and the microcontroller waits for this to happen so that later calibration steps are not triggered inadvertently.

If you find it fiddly to insert the cell while holding the tips closed, join the tips with a female-female jumper wire while inserting the cell. The handedness setting is kept in RAM, saving on wear to Flash memory. Since it is set every time power is applied, there is no need for non-volatile storage.

As the remaining calibration steps can be a bit fiddly, there is the option to skip them. You enter calibration by holding the tips together when prompted (Screen 3) or leaving them open to skip. If the tips are left open for about the first 10 seconds after power-up, the settings are the same as the original *SMD Test Tweezers*.

The next step is to adjust the value of the nominally 10kΩ series test resistor. The OLED displays CAL R+ and a countdown timer (Screen 4). Any time the tips are closed during this phase, the displayed value will increase, and the timer will reset.

This is followed by the CAL R- phase (Screen 5), which works much the same but allows the value to decrease. If any changes are made, the cycle repeats the CAL R+ and CAL R- steps until no more changes are made.

The OLED then prompts to save the value; again, touching the tips together before the displayed timeout is confirmation that the value is to be saved and, if this is done, a brief message is

Screen 2: at various times during setup, you may be prompted to RELEASE the Tweezers by opening the tips to ensure that multiple settings are not inadvertently made.

Screen 3: the first prompt is to complete the calibration process and is accompanied by a nominal five-second timer. If the tips are left open during this time, calibration is skipped.

CAL R+3
10005Ω

Screen 4: when the tips are closed on this screen, it will increase the saved value of the series test resistor in 1Ω steps. See Fig.5 for a flowchart explaining the process.

Screen 7: this screen shows while the value is saved to confirm that your selection has been acknowledged.

Screen 8: you are prompted to close the tips to calibrate their contact resistance. If you don't, the saved value is not changed.

Screen 9: the contact resistance is measured around 20 times to get an average. The value shown here is higher than the default value of 16Ω.

We are considering a more complicated *SMD Test Tweezers* design using a chip with, say, 14 pins. That might let us add new test modes and improve the existing ones.

Having these extra pins means that we could have multiple current-limiting resistors and thus a better choice of test current. As well as expanding the range, additional test resistors will also improve the overall accuracy.

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shown indicating this. These are seen in Screen 6 and Screen 7.

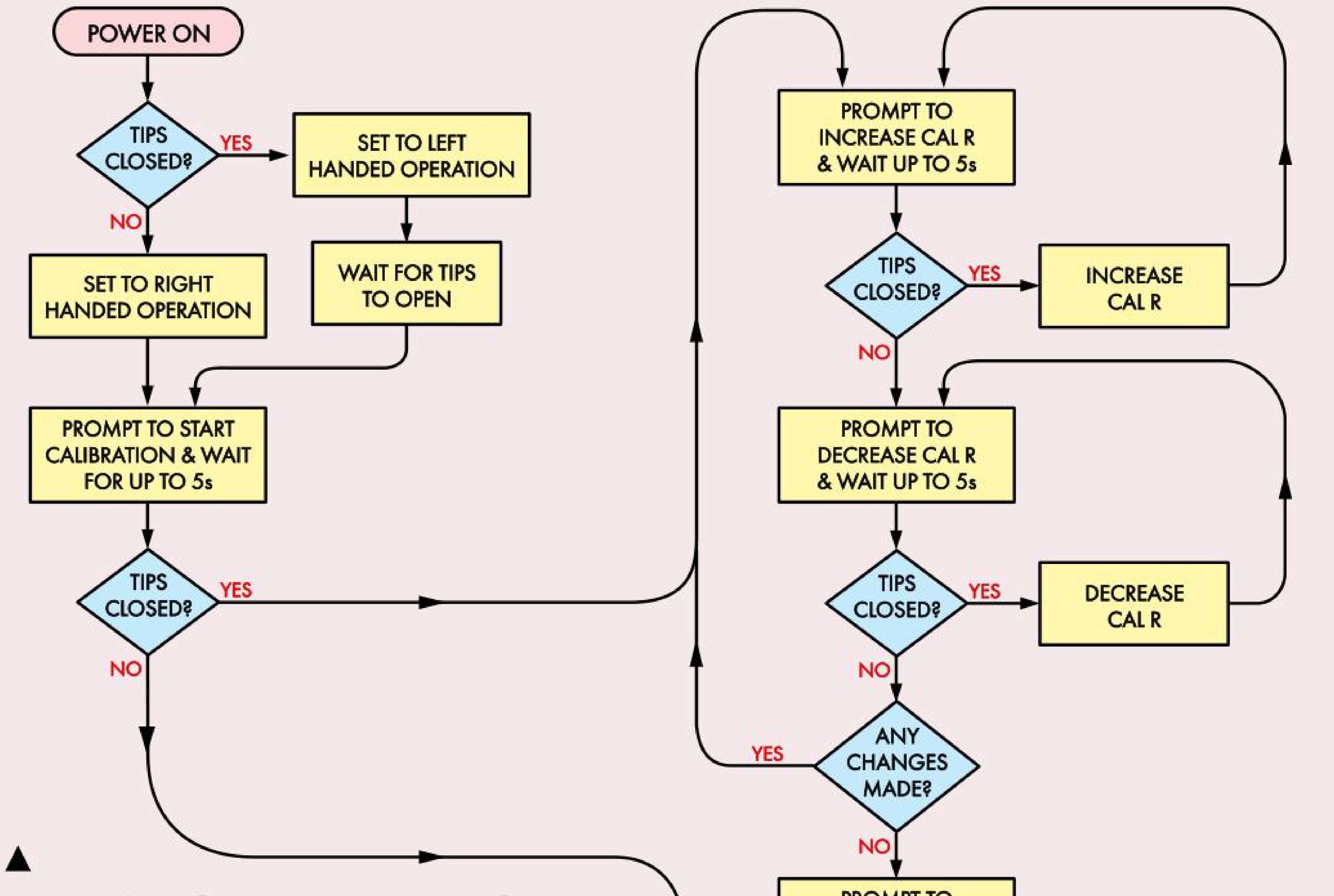
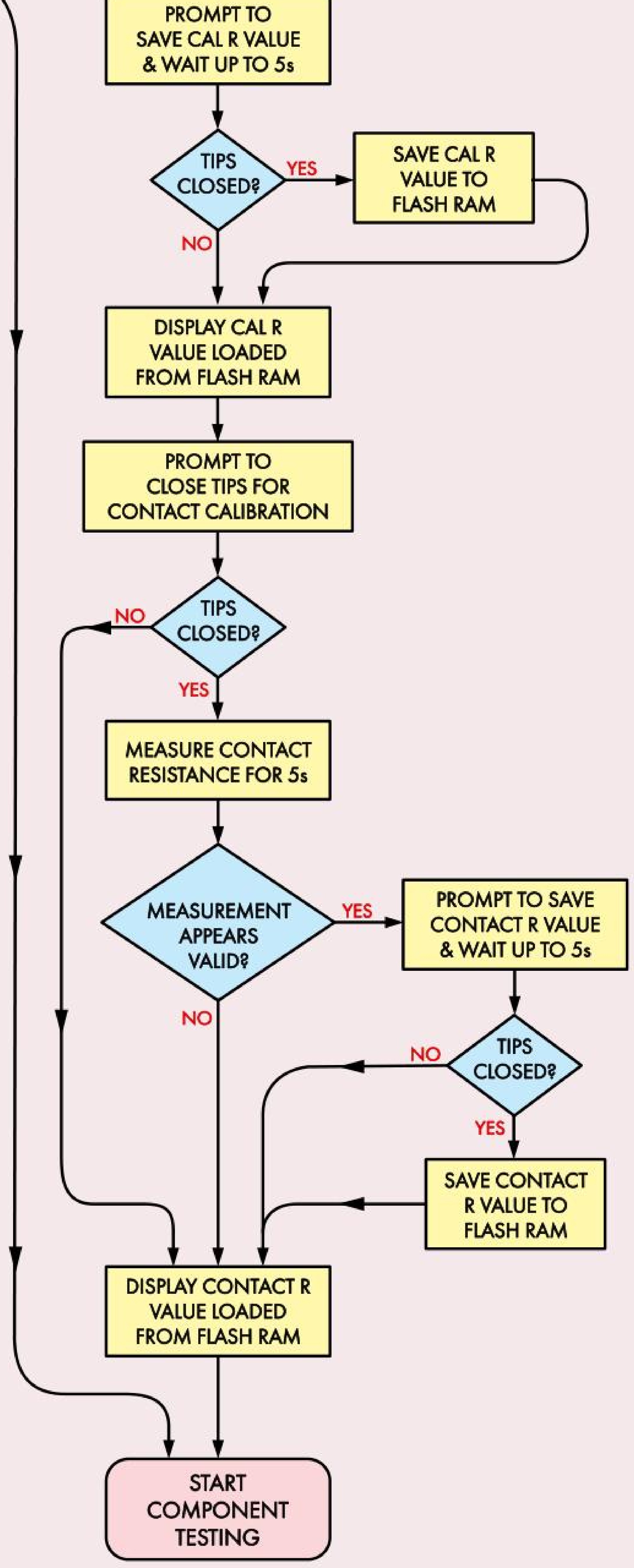
Finally, whether or not any changes are made or saved, the value of the series test resistor is freshly loaded from Flash memory and displayed for user confirmation. The next step – to set the contact resistance – is simpler, as this is measured rather than being entered.

Note that the timers shown on these screens are not high-precision. The internal timings vary depending on what is displayed (especially changing numbers, which take time to render). We've tried to make the countdown timers appear reasonably consistent as seconds, but they are not highly accurate.

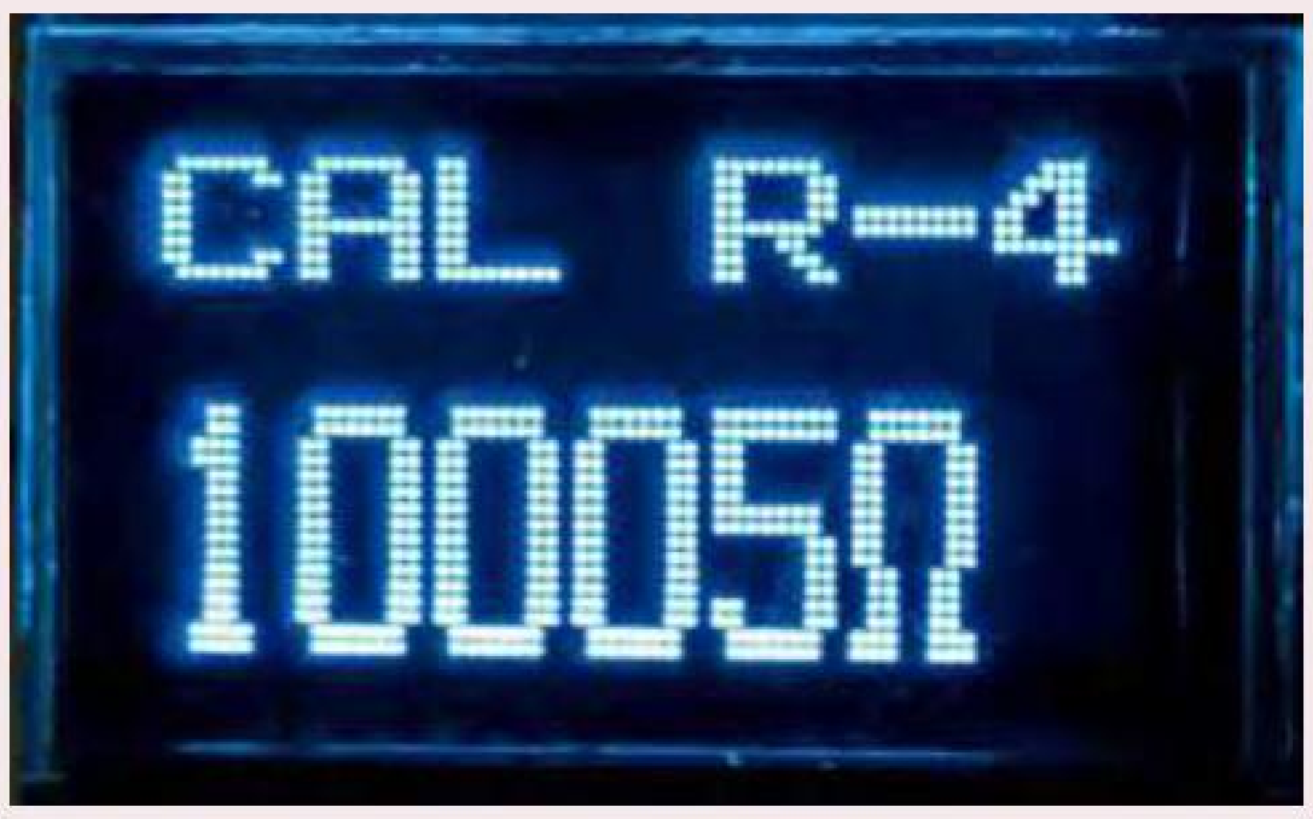
The prompt seen in Screen 8 is the start of the contact resistance calibration. When the tips are held together, Screen 9 is seen. This shows the measured contact resistance, averaged over several readings. The default value is 16Ω, as measured on our prototype.

If the tips are accidentally opened, the process aborts, and you will need to restart the calibration process to repeat it.

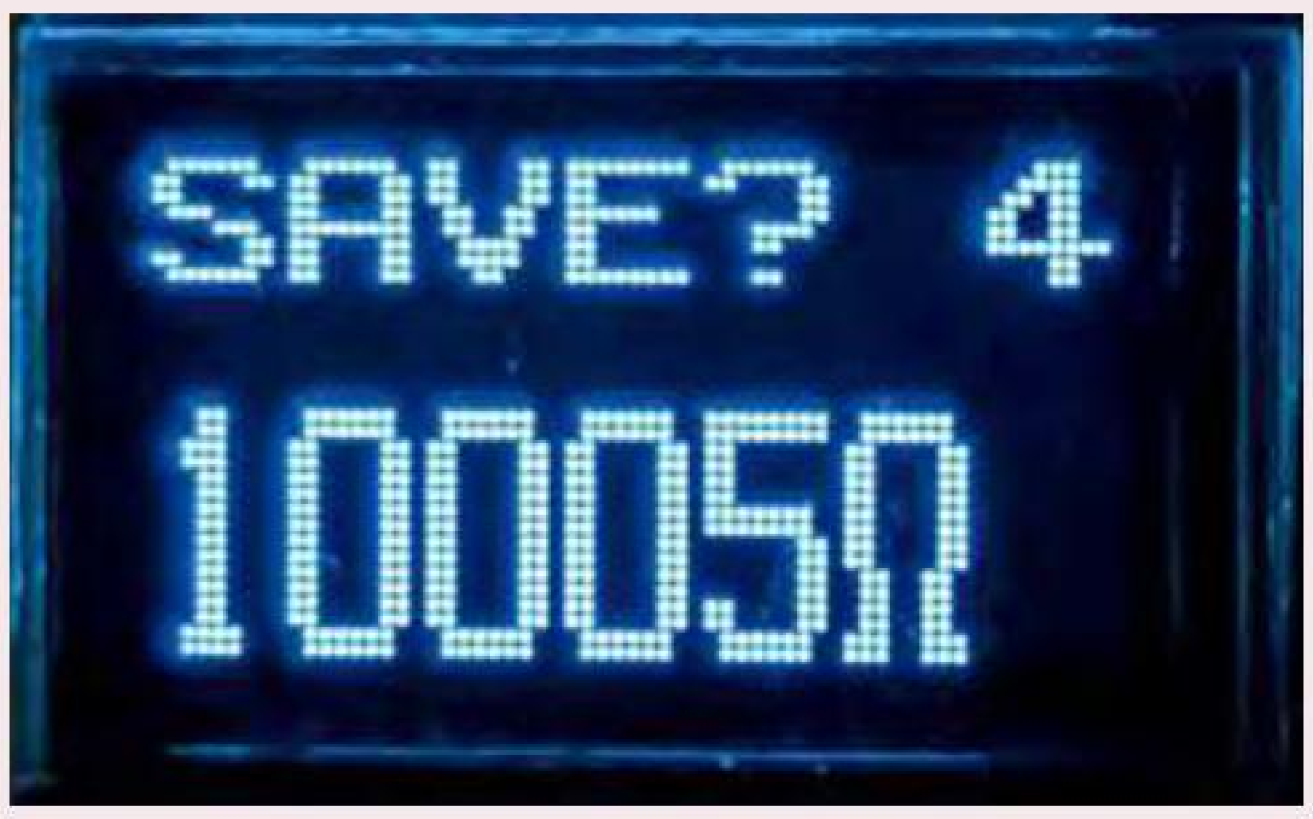
Otherwise, the averaged value is shown along with a prompt to save it, as seen in Screen 10. Close the tips to confirm or leave them open to allow the counter to time out. Screen 11 shows the actual value loaded from Flash memory.



POWER ON
TIPS CLOSED?
YES
SET TO LEFT HANDED OPERATION
NO
SET TO RIGHT HANDED OPERATION
WAIT FOR TIPS TO OPEN
PROMPT TO START CALIBRATION & WAIT FOR UP TO 5s
TIPS CLOSED?
YES
NO
PROMPT TO INCREASE CAL R & WAIT UP TO 5s
TIPS CLOSED?
YES
INCREASE CAL R
NO
PROMPT TO DECREASE CAL R & WAIT UP TO 5s
TIPS CLOSED?
YES
DECREASE CAL R
NO
ANY CHANGES MADE?
YES
NO
PROMPT TO SAVE CAL R VALUE & WAIT UP TO 5s
TIPS CLOSED?
YES
SAVE CAL R VALUE TO FLASH RAM
NO
DISPLAY CAL R VALUE LOADED FROM FLASH RAM
PROMPT TO CLOSE TIPS FOR CONTACT CALIBRATION
TIPS CLOSED?
NO
YES
MEASURE CONTACT RESISTANCE FOR 5s
MEASUREMENT APPEARS VALID?
YES
PROMPT TO SAVE CONTACT R VALUE & WAIT UP TO 5s
NO
TIPS CLOSED?
NO
YES
SAVE CONTACT R VALUE TO FLASH RAM
DISPLAY CONTACT R VALUE LOADED FROM FLASH RAM
START COMPONENT TESTING

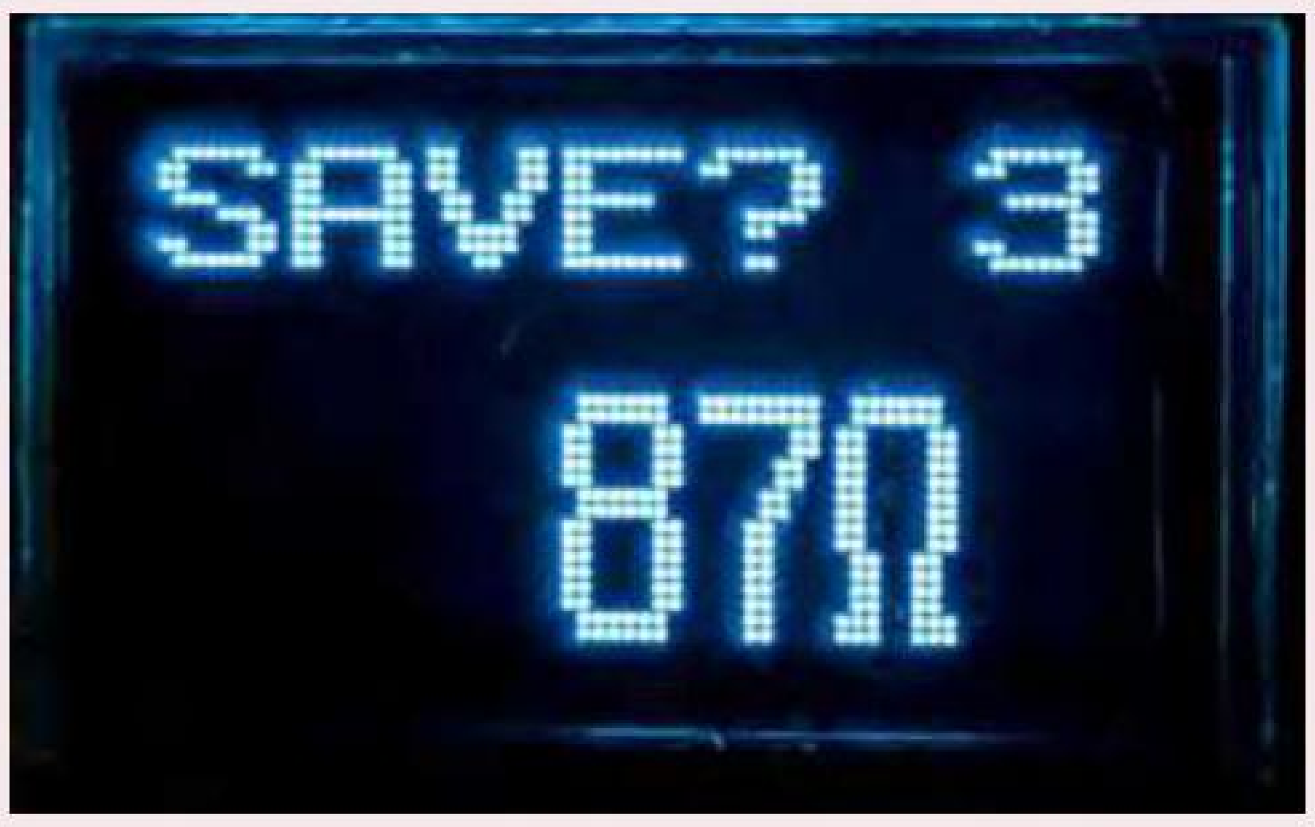
▲ **Fig.5: a flowchart representing the setup and calibration process that occurs when power is first applied to the Tweezers. It looks complicated, but it is simple to go through once you understand the concepts, and the Tweezers prompt you with what to do at each step.**


CAL R-4
10005Ω

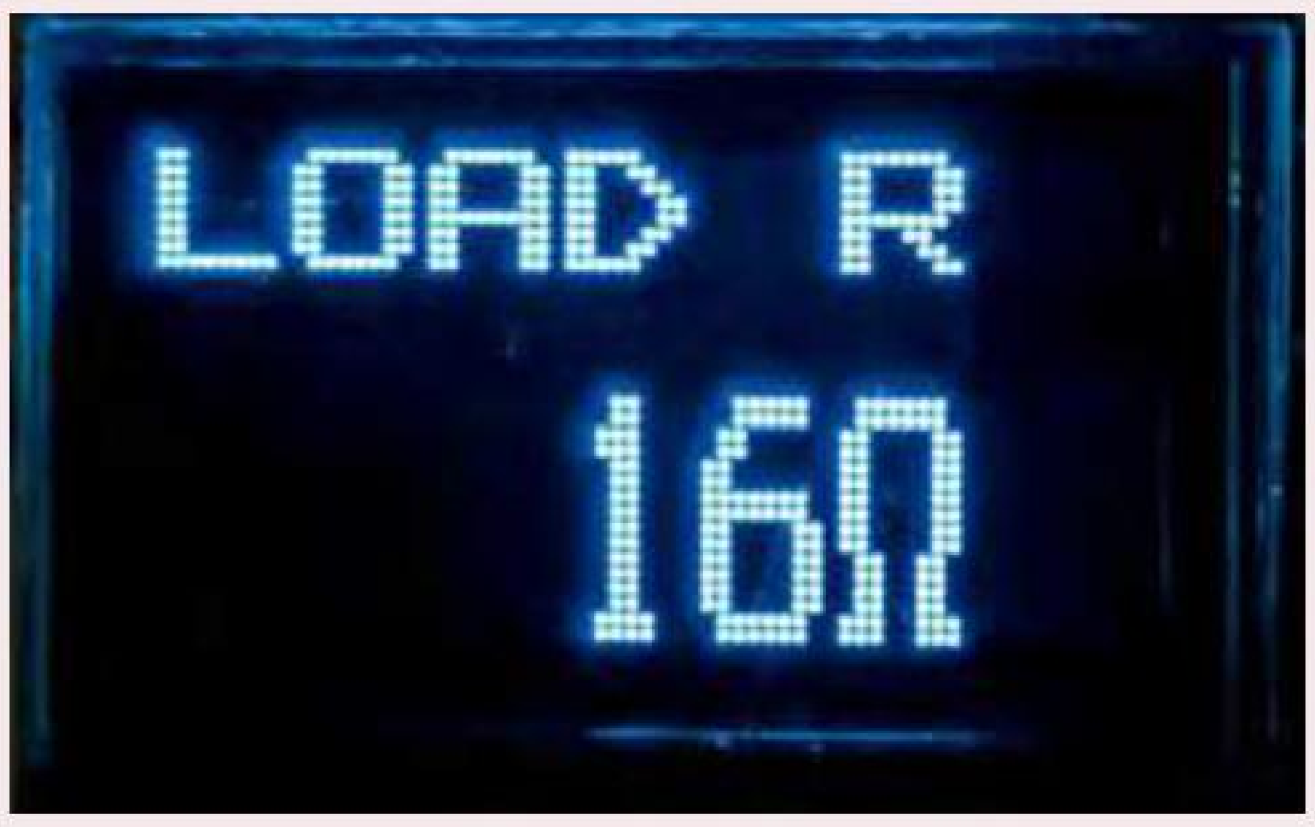
Screen 5: similarly, this screen allows the series test resistor value to be decreased. If any change occurs, these two steps are repeated until no change is detected.


SAVE? 4
10005Ω

Screen 6: this prompts you to confirm that you wish to save the entered value to non-volatile flash memory. Close the tips to do so.



Screen 10: if you don't get this message, the Tweezers have detected that the tips may have been opened, so the measured value is inaccurate.



Screen 11: finally, the actual value saved in flash memory is reloaded so that you can confirm that the saved value is correct.

Make it with Micromite

Phil Boyce – hands on with the mighty PIC-powered, BASIC microcontroller

Part 46: A PicoMite Smart-light Controller – Part 1

There are numerous smart-home devices available today, from lighting, security cameras and alarm systems to speakers, TVs, personal gadgets and even kitchen appliances. Typically, smart technology devices are controlled from a smartphone (or tablet) via an installed app. In the early days of smart tech, each manufacturer had its own eco-system, meaning that you could end up with several different apps, each of which controlled only certain devices, and they couldn't talk to each other.

As smart devices matured, their manufacturers incorporated compatibility with another branch of smart technology, voice control. Today, virtually all smart-home devices can be set up to be controlled with your voice using (at least) one of the three main systems: Google Home, Amazon Alexa and Apple Siri. Voice control effectively results in one common interface for all smart devices in a home, irrespective of the manufacturer.

It is worth noting here that some devices also include a touchscreen for user control. However, these tend to be limited to the more expensive kitchen appliances and smart speakers.

Now the dilemma – you may not always have your smartphone at hand to control, for example, a smart light. Likewise, it may not be suitable to use voice control (perhaps late at night) to instruct your smart speaker to switch off a smart light, and you certainly don't want the smart speaker confirming it has understood your command… or not! (This is even worse when the confirmation is spoken loudly.)

Granted, there are portable smart-button light switches available, but when you have numerous smart lights in the home these buttons can quickly become muddled up, especially when children like to play jokes with each other and swap them all around.

This led to an idea for a project; a low-cost PicoMite-based smart light controller. The concept was simple; incorporate a touchscreen so that the user can select a single smart light from a list of all the available lights and turn the light on or off, or even alter the brightness. How hard can that be?

Philips Hue

There are a lot of choices when it comes to smart lighting. My preference is the Philips Hue range. Yes, it's at the more expensive end of the price scale, however, their technology always works, and there are other benefits, as we shall see as we work through this project. I have found that a lot of other smart lighting that is available varies considerably in quality, often resulting in having to buy replacements earlier than expected. Just recently I had two LED strip-lights fail from a no-brand manufacturer. These were used as bedside lights, so they have now been replaced with Philips Hue strip-lights, meaning that the whole house (and garden) incorporates 100% Hue lighting.

Without going into too much detail here, the Philips Hue smart lights can be controlled either by BlueTooth, or by Wi-Fi (Zigbee). Bluetooth control is very limited, and hence won't provide the functionality that we're trying to achieve. On the other hand, Wi-Fi provides full control of the smart lights, but the version of Zigbee Philips adopted is overly complex to implement. However, Wi-Fi control is made much easier when a centralised low-cost Philips Hue Hub is built into the setup; something that Philips have documented reasonably well. So, rather than communicating directly with the smart lights via a version of the Zigbee protocol, the Hue Hub makes it possible for developers to use a standard Wi-Fi protocol (non-Zigbee) to control every aspect of the setup simply by communicating directly with the centralised Hub. Hence, by incorporating a Wi-Fi module into our project (such as the readily available ESP32), we should be able to achieve our goal of a *PicoMite Smart-light Controller*.

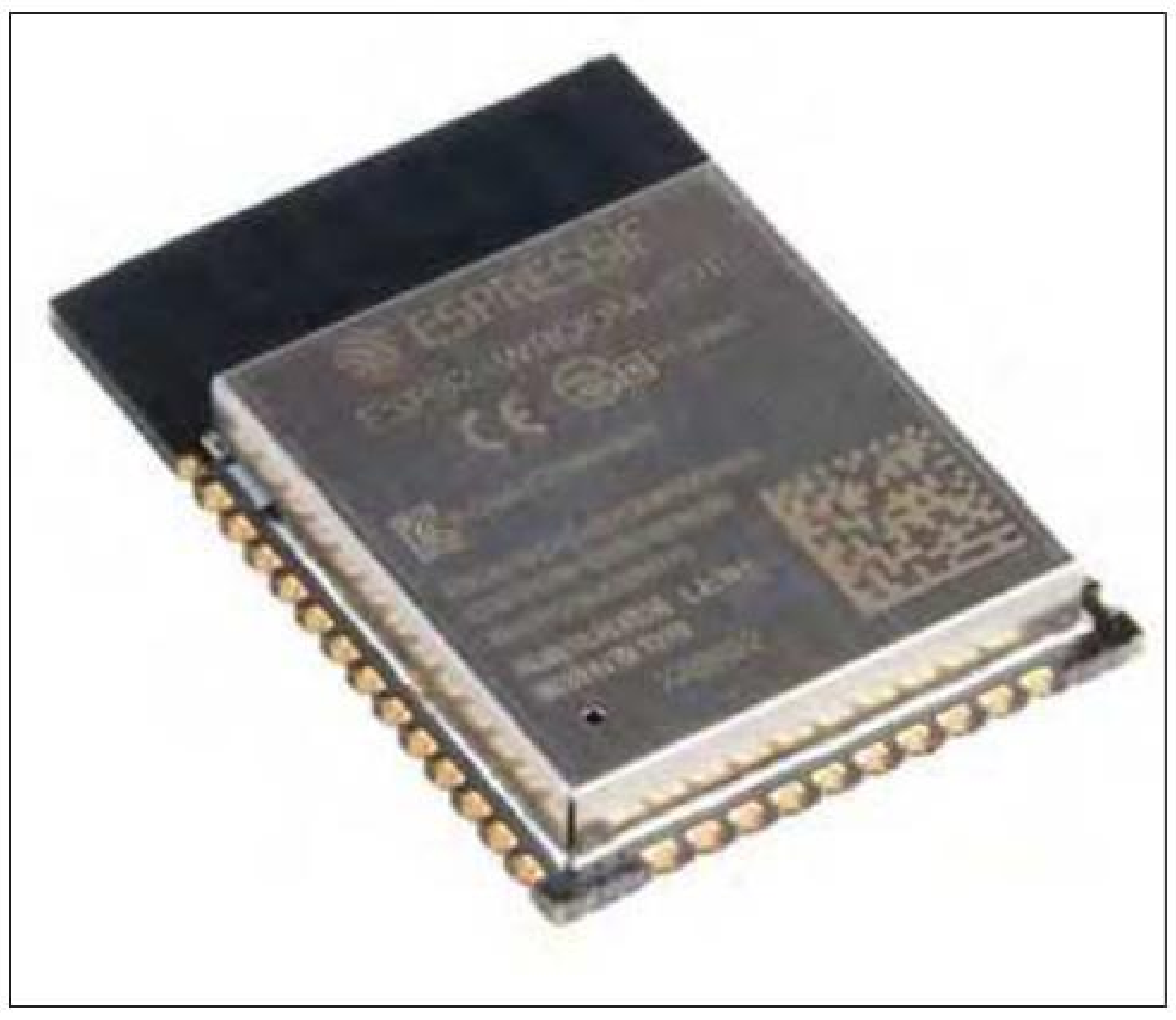


Fig.1. The surface-mount version of the ESP32-WROOM module.

The ESP32 module

There are many variations of the ESP32, both in terms of hardware and firmware. If you search online for 'ESP32 WROOM', you will see that there are two main variations available – a smaller surface-mount module (see Fig.1), and a slightly larger through-hole version (which is essentially an ESP32 surface-mount module mounted on a daughterboard that in turn provides header connections – see Fig.2). We recommend

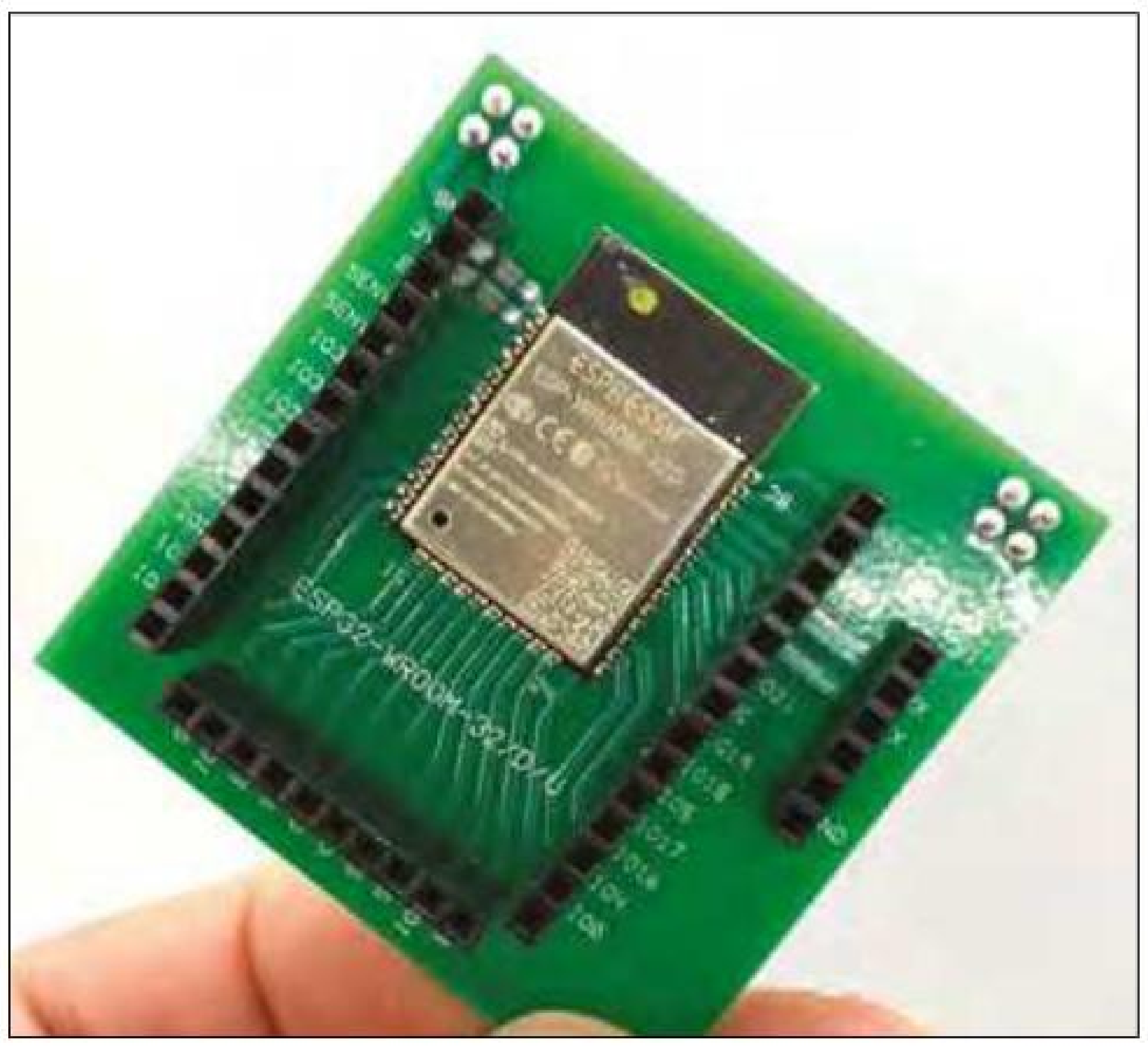


Fig.2. Through-hole version of the module is an SMD ESP32 mounted on a daughterboard with header connectors.

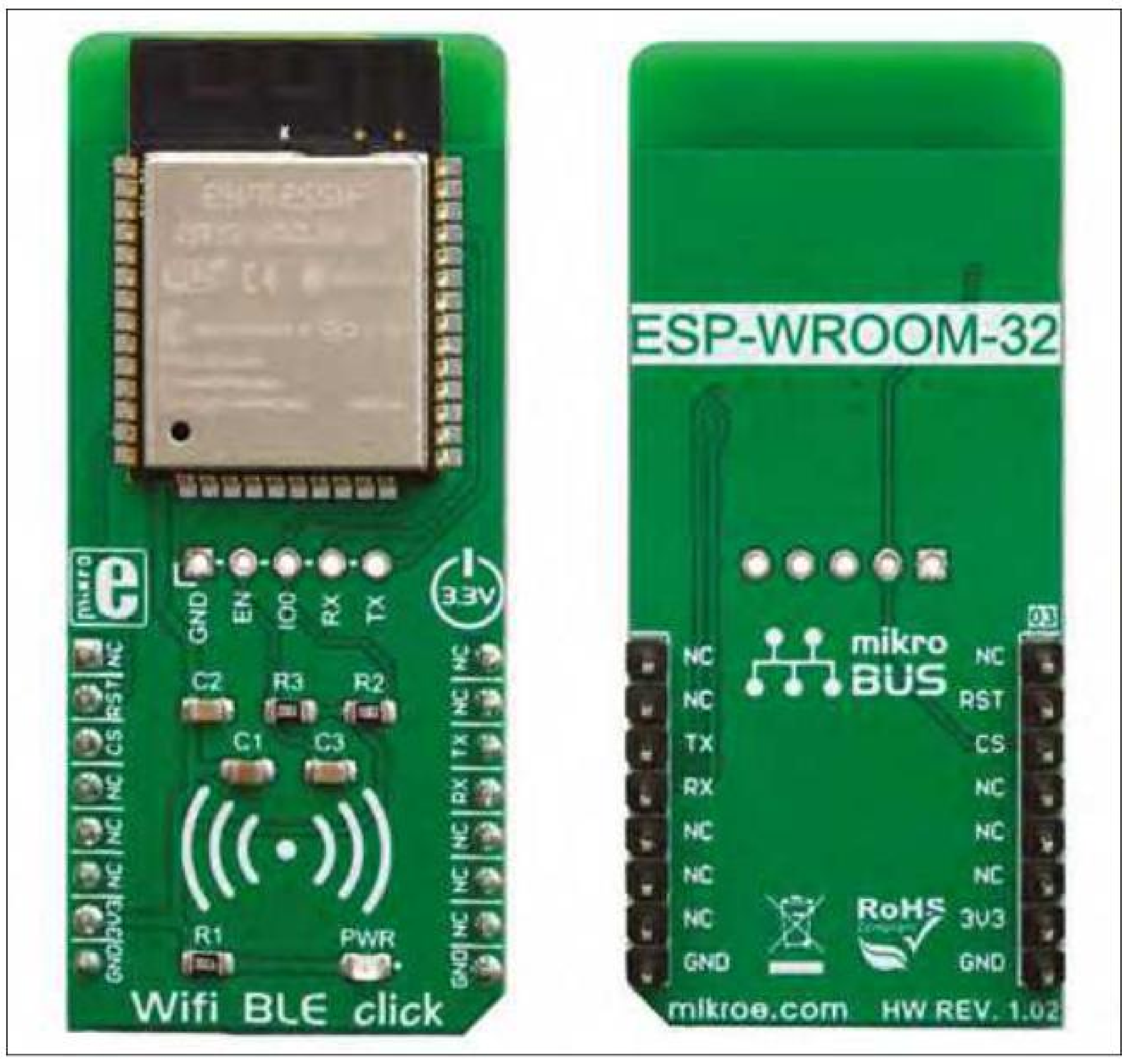
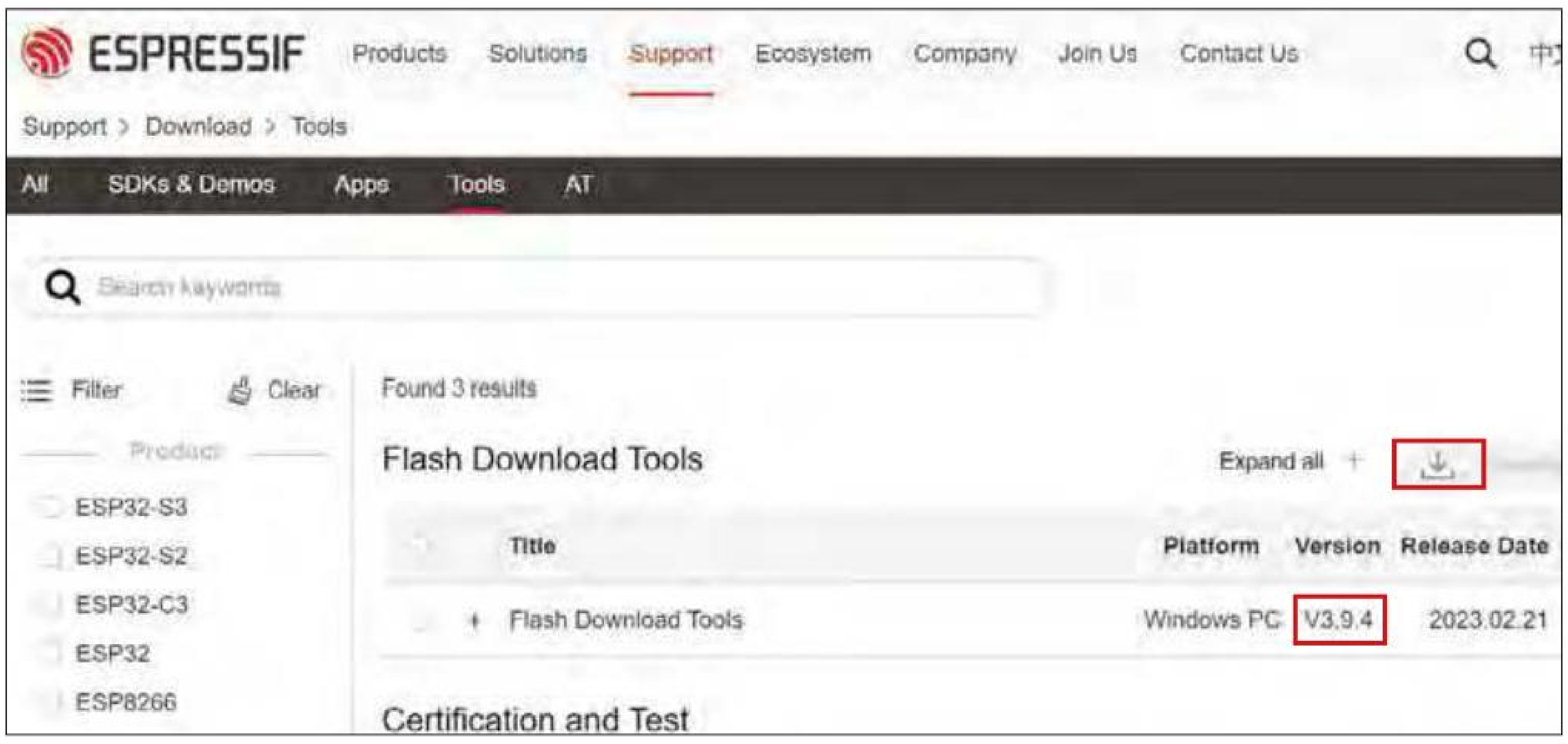

ESP-WROOM-32
GND
EN
IO0
RX
TX
3.3V
C2
R3
R2
C1
C3
R1
PWR
Wifi BLE click
mikro BUS
NC
TX
RX
GND
RST
CS
3V3
RoHS
mikroe.com
HW REV. 1.02

Fig.3. The MikroElektronika ESP32-WROOM module (MIKROE-3542) used in the development of the *PicoMite Smart-light Controller.*

that you go for the through-hole version of the ESP32 so that you can then easily connect it to the PicoMite using DuPont leads. At the time of development, I had a quantity of ESP32 WROOM Click modules (see Fig.3), so I used one of those for this project. As a guide, expect to pay around £10-£15 for an ESP32 WROOM module; slightly less if you're able to solder the SMD module onto a daughterboard yourself.

Turning to the ESP32's firmware, one version is available that incorporates an extensive set of AT commands. A good set of AT commands means that it is possible to gain access to the many features that are built into the ESP32. Furthermore, communicating via AT commands from MMBASIC is straightforward, which in turn means the program code will be much easier to follow. The specific AT firmware file we require is available for free download from the ESP32 manufacturer (Espressif). It will be used to overwrite whatever firmware comes pre-loaded in your ESP32 WROOM hardware.

Updating the ESP32 firmware can be challenging, so in *Part 1* of this project we will guide you through the process step-by-step. It is important to note that updating the ESP32 WROOM with the relevant AT firmware is essential as it will guarantee that all the AT commands used in the project's program code will be recognised by the ESP32, enabling successful Wi-Fi communication with the Philips Hue hub. Other versions of the ESP firmware will probably have some commands missing and may not work.


ESPRESSIF
Products
Solutions
Support
Ecosystem
Company
Join Us
Contact Us
Support > Download > Tools
All
SDKs & Demos
Apps
Tools
AT
Search keywords
Filter
Clear
Product
ESP32-S3
ESP32-S2
ESP32-C3
ESP32
ESP8266
Expand all +

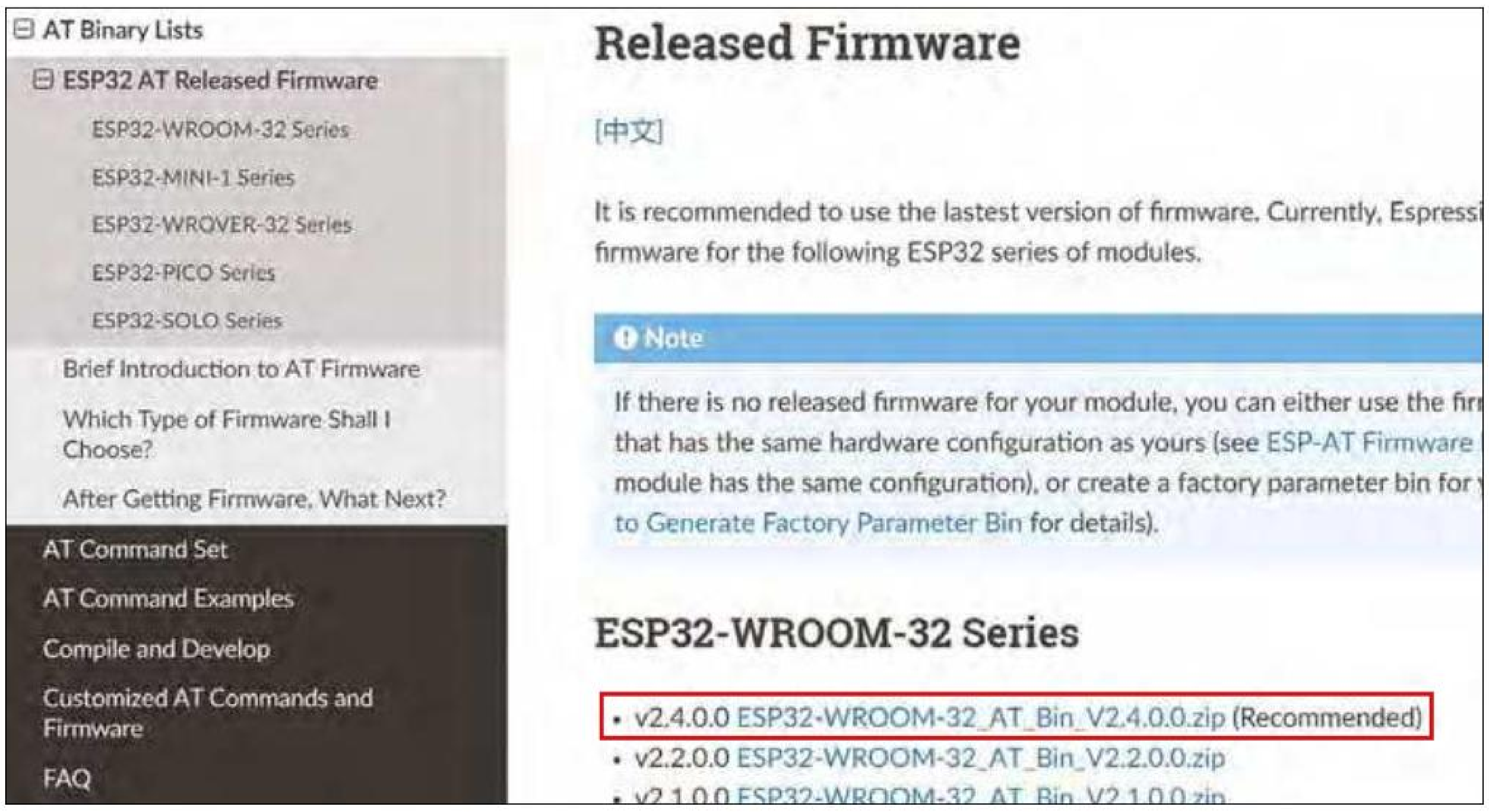
Found 3 results

Flash Download Tools

Title	Platform	Version	Release Date
Flash Download Tools	Windows PC	V3.9.4	2023.02.21

Certification and Test

Fig.4. The ESP Flash Tool can be downloaded from Espressif's website. It makes upgrading the ESP32 firmware a much easier task.


AT Binary Lists
ESP32 AT Released Firmware
ESP32-WROOM-32 Series
ESP32-MINI-1 Series
ESP32-WROVER-32 Series
ESP32-PICO Series
ESP32-SOLO Series
Brief Introduction to AT Firmware
Which Type of Firmware Shall I Choose?
After Getting Firmware, What Next?
AT Command Set
AT Command Examples
Compile and Develop
Customized AT Commands and Firmware
FAQ
[中文]

Released Firmware

It is recommended to use the lastest version of firmware. Currently, Espressi
firmware for the following ESP32 series of modules.

Note

If there is no released firmware for your module, you can either use the fir
that has the same hardware configuration as yours (see ESP-AT Firmware
module has the same configuration), or create a factory parameter bin for
to Generate Factory Parameter Bin for details).

ESP32-WROOM-32 Series

- v2.4.0.0 ESP32-WROOM-32_AT_Bin_V2.4.0.0.zip (Recommended)
- v2.2.0.0 ESP32-WROOM-32_AT_Bin_V2.2.0.0.zip
- v2.1.0.0 ESP32-WROOM-32_AT_Bin_V2.1.0.0.zip

Fig.5. The latest version of the required firmware file (zipped folder) is shown at the top of the list. Here, it is version **v2.4.0.0 ESP32-WROOM-32_AT_Bin_V2.4.0.0.zip (Recommended)**

Let's get started.

Updating the ESP32 firmware

The five steps to update the ESP32 module with the AT firmware are as follows:

1. Download ESP32 Flash tool from Espressif
2. Download AT firmware file from Espressif
3. Connect ESP32 WROOM module to PC
4. Run Flash tool to upload the AT firmware
5. Test the firmware loaded successfully.

To perform the above steps you will need the following items:

- Windows PC (connected to the Internet)
- USB-to-Serial module
- Jumper leads (DuPont)
- A mini breadboard.

Note that the ESP32 is a 3.3V device which pulls more than 200mA at peak current (although it does operate lower than this most of the time). To handle these peak currents, you may require a beefier 3.3V supply than a USB-to-Serial module can cope with. Our recommendation is to use the Raspberry Pi Pico's main 3.3V output (on pin 36) as it is capable of safely supplying 300mA.

We will now work through the five firmware update steps.

Step 1: Download ESP Flash Tool

The ESP32 Flash Tool is available for free download from the manufacturer's website. However, it currently only supports the Windows platform. So, from a Windows computer, visit **https://bit.ly/pe-may23-esp** and click on the link to download the Flash Download Tools (see Fig.4). This will download a zipped folder (about 16MB), and at the time of writing, the version number was V3.9.4. Once downloaded, extract the files and you will then see the main program that we will be using: **flash_download_tool_3.9.4.exe**

Step 2: Download AT Firmware file

The required AT Firmware file can also be downloaded from the Espressif website. Visit: **https://bit.ly/pe-may23-at** and click the link at the top of the list to download a zipped folder (about 22MB). At the time of writing, this was: **v2.4.0.0 ESP32-WROOM-32_AT_Bin_V2.4.0.0.zip (Recommended)** – see Fig.5. Extract the files and make a note of where the extracted folder is (probably in your Downloads).

Step 3: Connecting the ESP32

The ESP32 module has three serial ports (UART0, UART1 and UART2) – we will

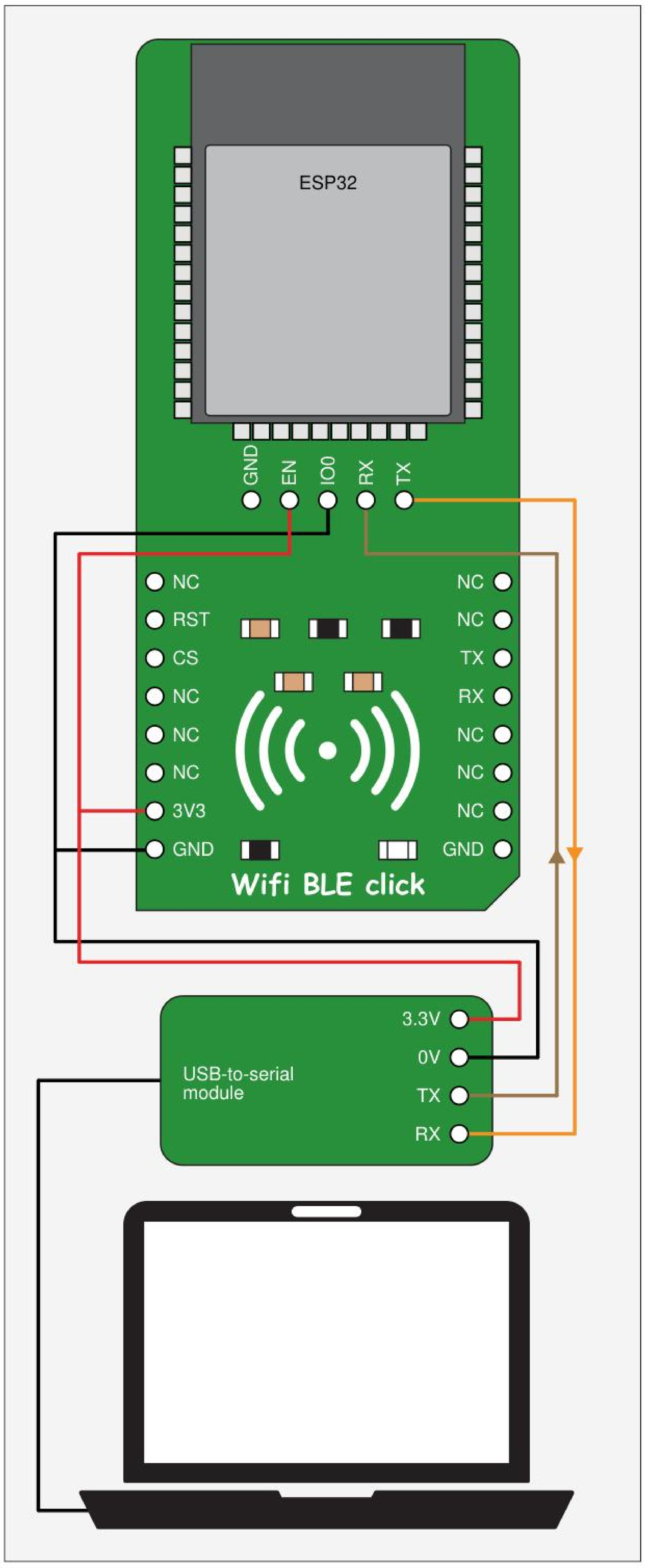

ESP32
GND
EN
IO0
RX
TX
NC
RST
CS
NC
NC
NC
3V3
GND
NC
NC
TX
RX
NC
NC
NC
GND
Wifi BLE click
3.3V
0V
TX
RX
USB-to-serial module

Fig.6. The six connections shown here connect the USB-to-Serial module to the MIKROE ESP32 module and put it into Bootloader mode. It connects to UART0 on the ESP32.

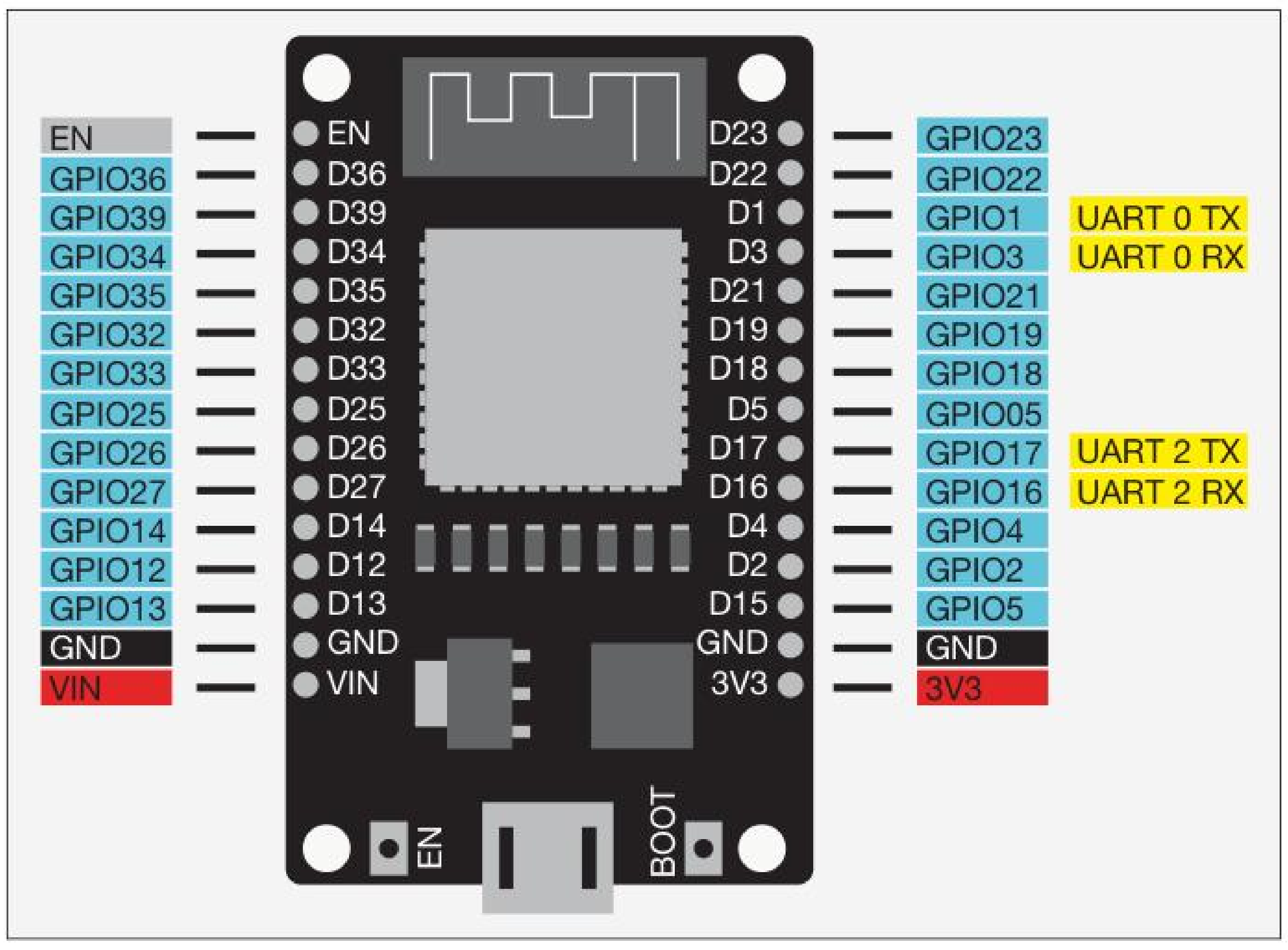

EN
GPIO36
GPIO39
GPIO34
GPIO35
GPIO32
GPIO33
GPIO25
GPIO26
GPIO27
GPIO14
GPIO12
GPIO13
GND
VIN
EN
D36
D39
D34
D35
D32
D33
D25
D26
D27
D14
D12
D13
GND
VIN
D23
D22
D1
D3
D21
D19
D18
D5
D17
D16
D4
D2
D15
GND
3V3
GPIO23
GPIO22
GPIO1
GPIO3
GPIO21
GPIO19
GPIO18
GPIO05
GPIO17
GPIO16
GPIO4
GPIO2
GPIO5
GND
3V3
UART 0 TX
UART 0 RX
UART 2 TX
UART 2 RX
EN
BOOT

Fig.7. (Right) Pin labelling on a typical ESP32 through-hole module. Positions of pins may vary between different manufacturers.

use two of them. To flash the firmware file into the ESP32 we have to connect our USB-to-Serial module to UART0. On the MIKROE ESP32 module, UART0 is accessed via a dedicated row of pins (along with the other pins we need to connect for flashing the firmware). Fig.6 shows how to connect the MIKROE ESP32 module to the USB-to-Serial module.

If your module does not have a dedicated set of pins for flashing the firmware, then all the relevant pins on the module will be labelled with GPIO numbers (plus power and others for basic control, such as 'Enable') – Fig.7 shows an example. You will need to connect three GPIO pins as follows; along with 3.3V power (ideally 300mA capable) and the Enable pin:

ESP	USB
GPIO0	0V
GPIO1(TX)	Rx
GPIO3(Rx)	Tx
EN	3.3V
0V	0V
3.3V	3.3V (ideally 300mA)

Note: when GPIO0 is low (0V), the ESP32 enters 'Bootloader' mode, and this is exactly what we need to be able to load the new ESP32 AT firmware. However, when GPIO0 is high (3.3V), the ESP32 will be in normal execution mode. GPIO0 has an internal pull-up resistor, so when this pin is unconnected, the ESP32 is in Normal mode.

Now that the ESP32 is connected to the computer, we can load the new AT firmware.

Step 4: Upload Firmware

Before running the ESP Flash Tool, make sure that you close any open terminal app program. This ensures that Windows frees up any COM port that would otherwise be assigned to to the USB-to-Serial module.

To launch the ESP Flash Tool, go to the folder unzipped in Step 1 that contains the executable file: **flash_download_tool_3.9.4.exe**

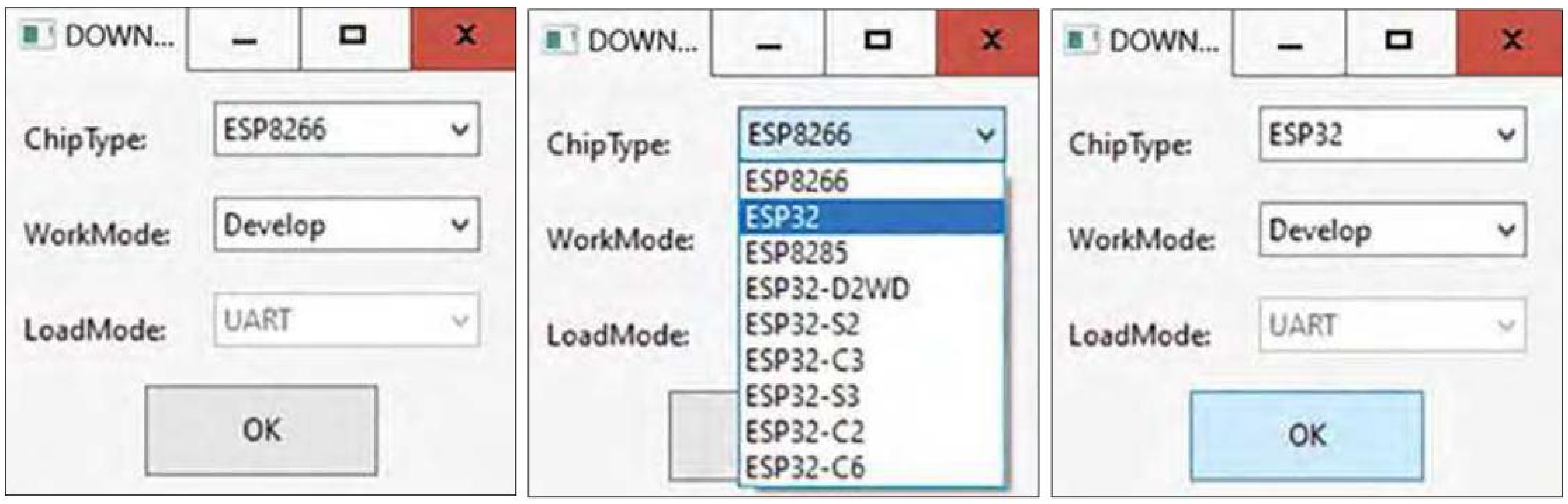
Launch it, and the initial screen will be as shown in Fig.8a. The top option (Chip Type) will be set to 'ESP8266', and this will need changing. Click on the drop-down arrow (Fig.8b) and select 'ESP32' so that the screen now looks like Fig.8c. The other two options should be left set to 'Develop' and 'UART'.

On clicking the 'OK' button, you will see a screen like that shown in Fig.9. At the bottom, you should select the appropriate COM port (the one Windows assigns to the USB-to-Serial module) and the correct baud rate (115200).

Next, in the top empty line near the top of the screen, select the three dots to open a file browser and select the extracted file **factory_WROOM-32.bin** from the firmware folder from Step 2 in your Downloads folder: **Downloads\ESP32-WROOM-32_AT_Bin_V2.4.0.0\ESP32-WROOM-32-V2.4.0.0\factory**

In the smaller empty box on the right, enter the value `0x00`. Now check all the other settings so they match that shown in Fig.10 (in particular, ensure 'DoNotChgBin' is ticked).

With the settings configured, press the 'START' button. This will start the uploading process with a green progress bar at the bottom of the screen (Fig.11). Note that the 'DetectedInfo' box (left of screen-centre) will also show some information, along with some other data shown in the box below that is not relevant, but confirms things are happening as expected.

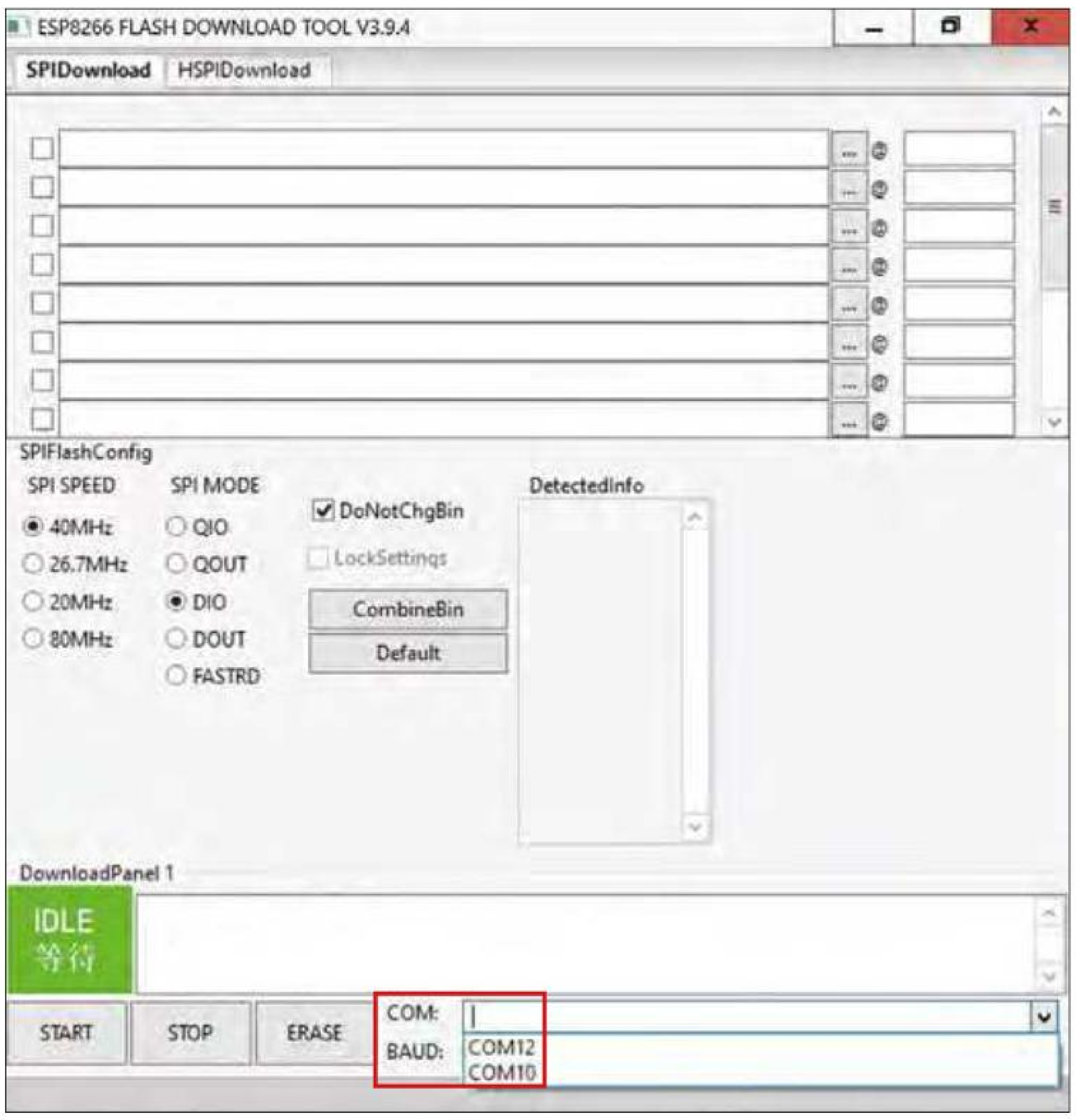

DOWN...
OK
DOWN...
ESP8266
ESP32
ESP8285
ESP32-D2WD
ESP32-S2
ESP32-C3
ESP32-S3
ESP32-C2
ESP32-C6
DOWN...
OK

ChipType: ESP8266
WorkMode: Develop
LoadMode: UART

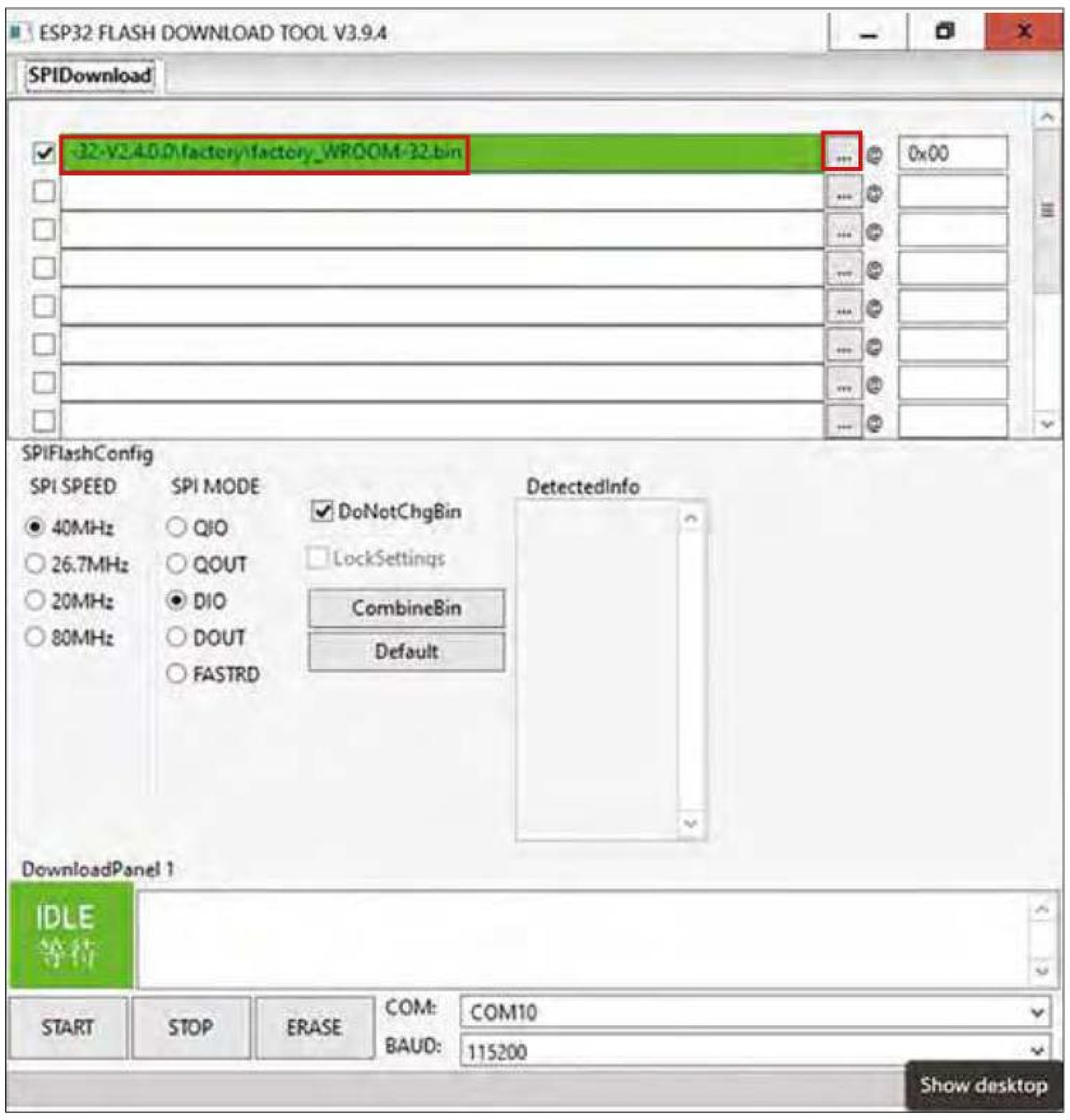
ChipType: ESP8266
WorkMode:
LoadMode:

ChipType: ESP32
WorkMode: Develop
LoadMode: UART

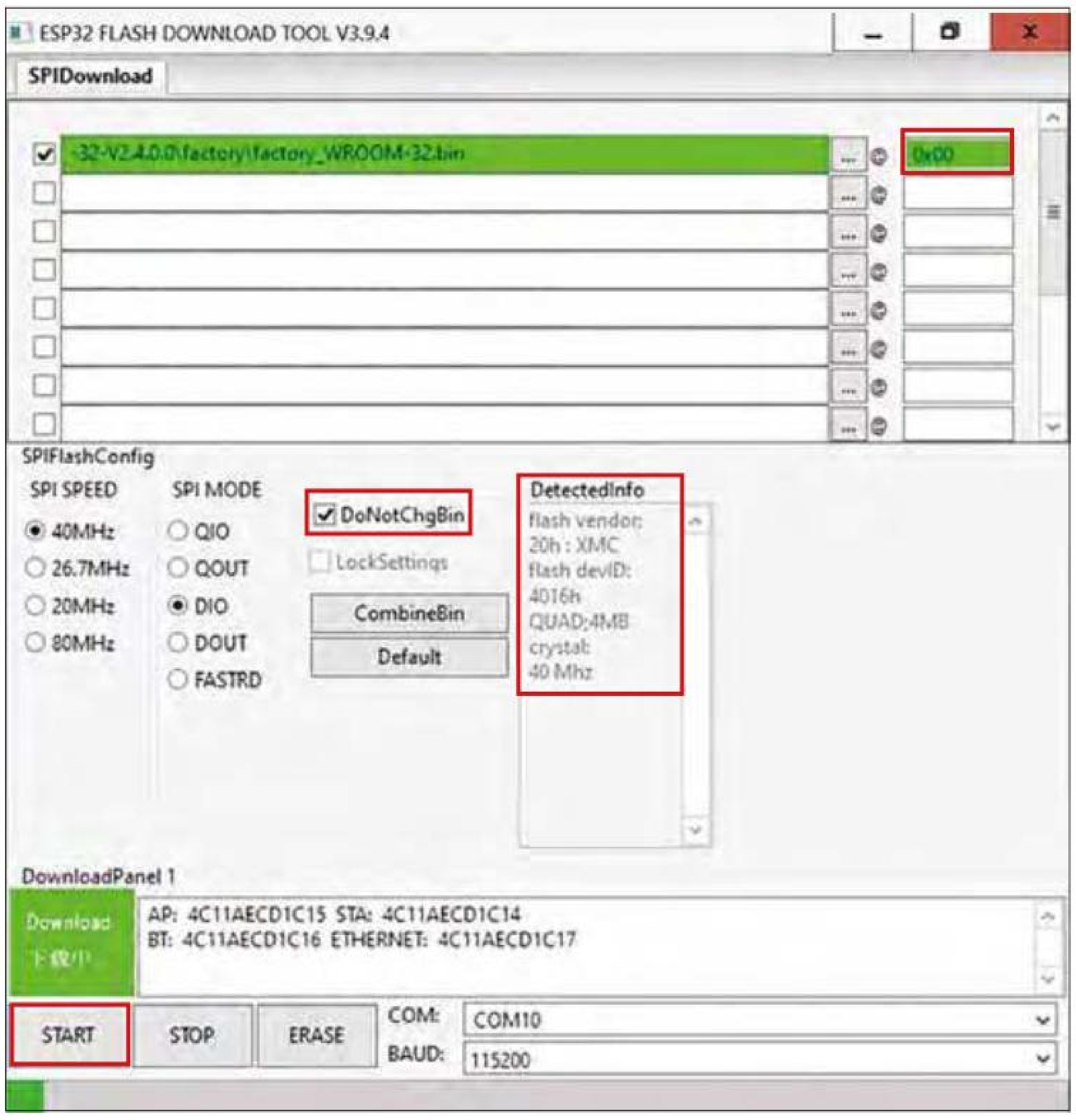
Fig.8. On launching the ESP Flash Tool (left to right): a) change from the default ESP8266 option; b) use the drop-down; and c) select the ESP32 option.


ESP8266 FLASH DOWNLOAD TOOL V3.9.4
SPIDownload
HSPIDownload
SPIFlashConfig
SPI SPEED
SPI MODE
DetectedInfo
CombineBin
Default
LockSettings
DownloadPanel 1
IDLE
等待
START
STOP
ERASE

SPI SPEED: ● 40MHz ○ 26.7MHz ○ 20MHz ○ 80MHz
SPI MODE: ○ QIO ○ QOUT ● DIO ○ DOUT ○ FASTRD
☑ DoNotChgBin
☐ LockSettings
COM: |
BAUD:
COM12
COM10


ESP32 FLASH DOWNLOAD TOOL V3.9.4
SPIDownload
SPIFlashConfig
SPI SPEED
SPI MODE
DetectedInfo
CombineBin
Default
DownloadPanel 1
IDLE
等待
START
STOP
ERASE
Show desktop

☑ -32-V2.4.0.0\factory\factory_WROOM-32.bin @ 0x00
SPI SPEED: ● 40MHz ○ 26.7MHz ○ 20MHz ○ 80MHz
SPI MODE: ○ QIO ○ QOUT ● DIO ○ DOUT ○ FASTRD
☑ DoNotChgBin
☐ LockSettings
COM: COM10
BAUD: 115200


ESP32 FLASH DOWNLOAD TOOL V3.9.4
SPIDownload
SPIFlashConfig
SPI SPEED
SPI MODE
DetectedInfo
CombineBin
Default
DownloadPanel 1
Download
下载中
START
STOP
ERASE

☑ -32-V2.4.0.0\factory\factory_WROOM-32.bin @ 0x00
SPI SPEED: ● 40MHz ○ 26.7MHz ○ 20MHz ○ 80MHz
SPI MODE: ○ QIO ○ QOUT ● DIO ○ DOUT ○ FASTRD
☑ DoNotChgBin
☐ LockSettings

DetectedInfo:
flash vendor:
20h : XMC
flash devID:
4016h
QUAD;4MB
crystal:
40 Mhz

AP: 4C11AECD1C15 STA: 4C11AECD1C14
BT: 4C11AECD1C16 ETHERNET: 4C11AECD1C17

COM: COM10
BAUD: 115200

Fig.9. (Left-top) The main screen of the ESP Flash Tool program. The COM port and BAUD rate need to be set so it connects to the USB-to-Serial module correctly.

Fig.10. (Left-middle) The ESP Flash Tool program needs to be loaded with the AT Firmware File. The three dots highlighted will open a file browser from where you point to the location of the firmware .BIN file downloaded as part of Step 2.

Fig.11. (Left-bottom) The upload process is triggered by pressing the 'START' button. Progress is indicated by the green progress bar at the bottom of the screen.

After a short while, the upload process will finish, indicated by a full green progress bar, and a light-blue button in lower left corner stating 'FINISH'. If you look at the 'black screen' behind the main window, you will also see some text, and the last line also confirms the process is finished (see Fig.12).

The ESP Flash Tool program can now be closed, ready for the next step.

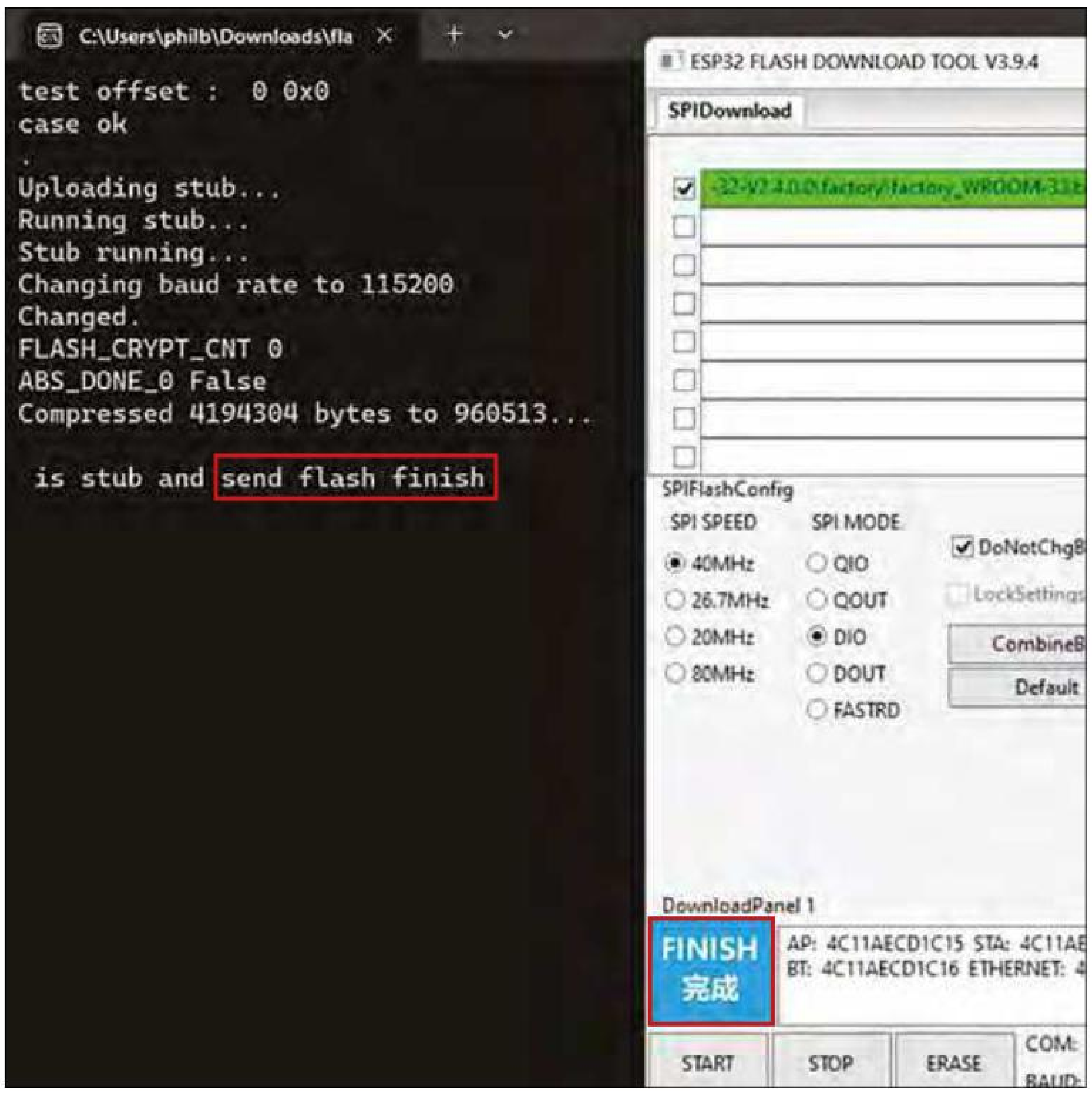
Step 5: Testing

To test that the ESP32 firmware upload has been successful, we need to alter the way that the ESP32 module is connected. We now need to connect our USB-to-Serial module to UART2 on the ESP32, and also ensure that we don't put the ESP32 into Bootloader mode by removing the connection to GPIO0 (the internal pull-up resistor on this pin will ensure that the ESP32 is in Normal mode). Now make the four connections shown in Fig.13 and then launch your terminal app to communicate directly with the ESP32 and begin sending AT commands to it.

For the following demonstration, we will be using TeraTerm as our terminal app. Begin by connecting TeraTerm to the COM port that Windows assigns to the USB-to-Serial module. Note that there are two settings within TeraTerm that you may need to alter:

1. In the 'Setup-Terminal…' menu, ensure 'Receive' is set to 'CR', 'Transmit' is set to 'CR+LF', and 'Echo' is unticked (see Fig.14).
2. In the 'Setup-Serial port…' menu, ensure that 'Speed:' is set to 115200, and the other settings on this page match those shown in Fig.15.

With the settings configured correctly, simply type `AT` and then press enter. The ESP32 should respond with `OK`. If so, then all is good. However, if you don't see the `OK` response then first check the four connections (Fig.13), and then re-check the terminal app settings (Fig.14 and Fig.15).


C:\Users\philb\Downloads\fla
ESP32 FLASH DOWNLOAD TOOL V3.9.4
SPIDownload
SPIFlashConfig
SPI SPEED
SPI MODE
CombineB
Default
DownloadPanel 1
FINISH
完成
START
STOP
ERASE
COM:
BAUD:

```
test offset :  0 0x0
case ok
.
Uploading stub...
Running stub...
Stub running...
Changing baud rate to 115200
Changed.
FLASH_CRYPT_CNT 0
ABS_DONE_0 False
Compressed 4194304 bytes to 960513...

 is stub and send flash finish
```

☑ -32-V2.4.0.0\factory\factory_WROOM-32.b
SPI SPEED: ● 40MHz ○ 26.7MHz ○ 20MHz ○ 80MHz
SPI MODE: ○ QIO ○ QOUT ● DIO ○ DOUT ○ FASTRD
☑ DoNotChgB
☐ LockSettings
AP: 4C11AECD1C15 STA: 4C11AE
BT: 4C11AECD1C16 ETHERNET: 4

Fig.12. When the upload is complete, the screen will display a blue FINISH message in the lower-left corner.

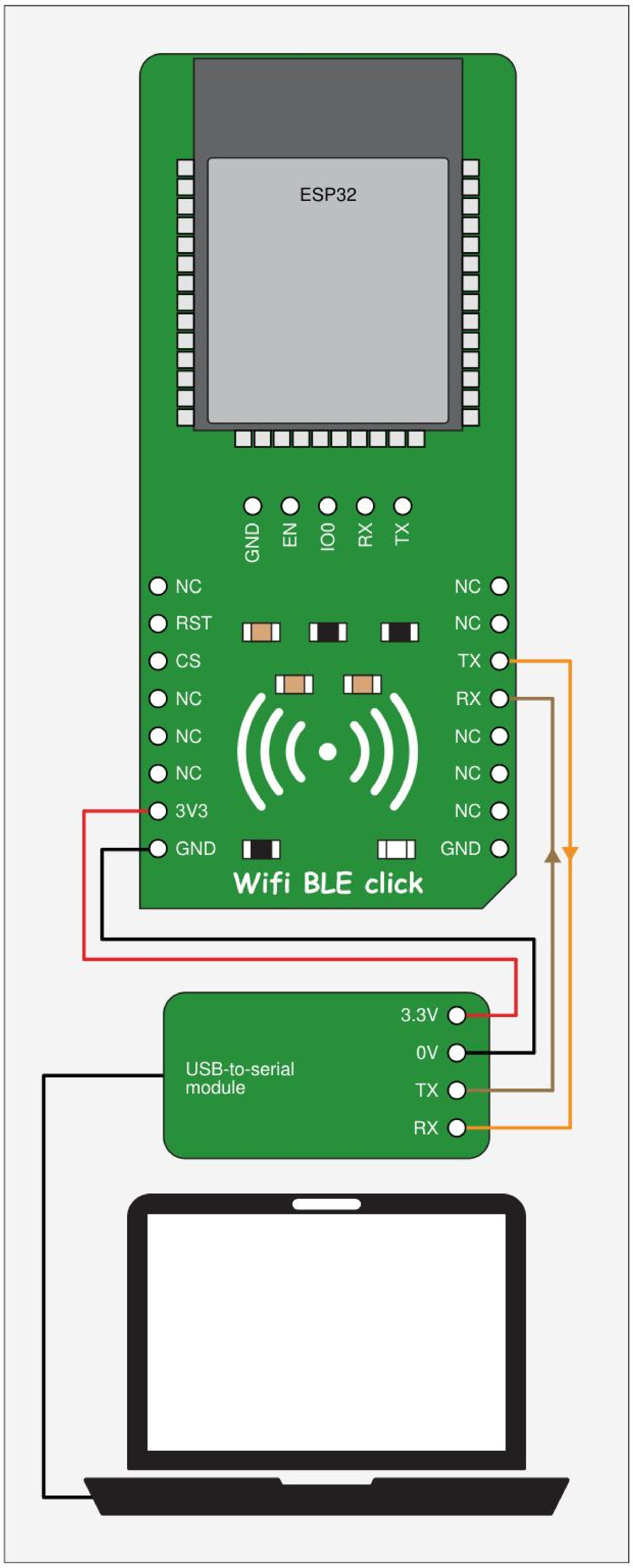
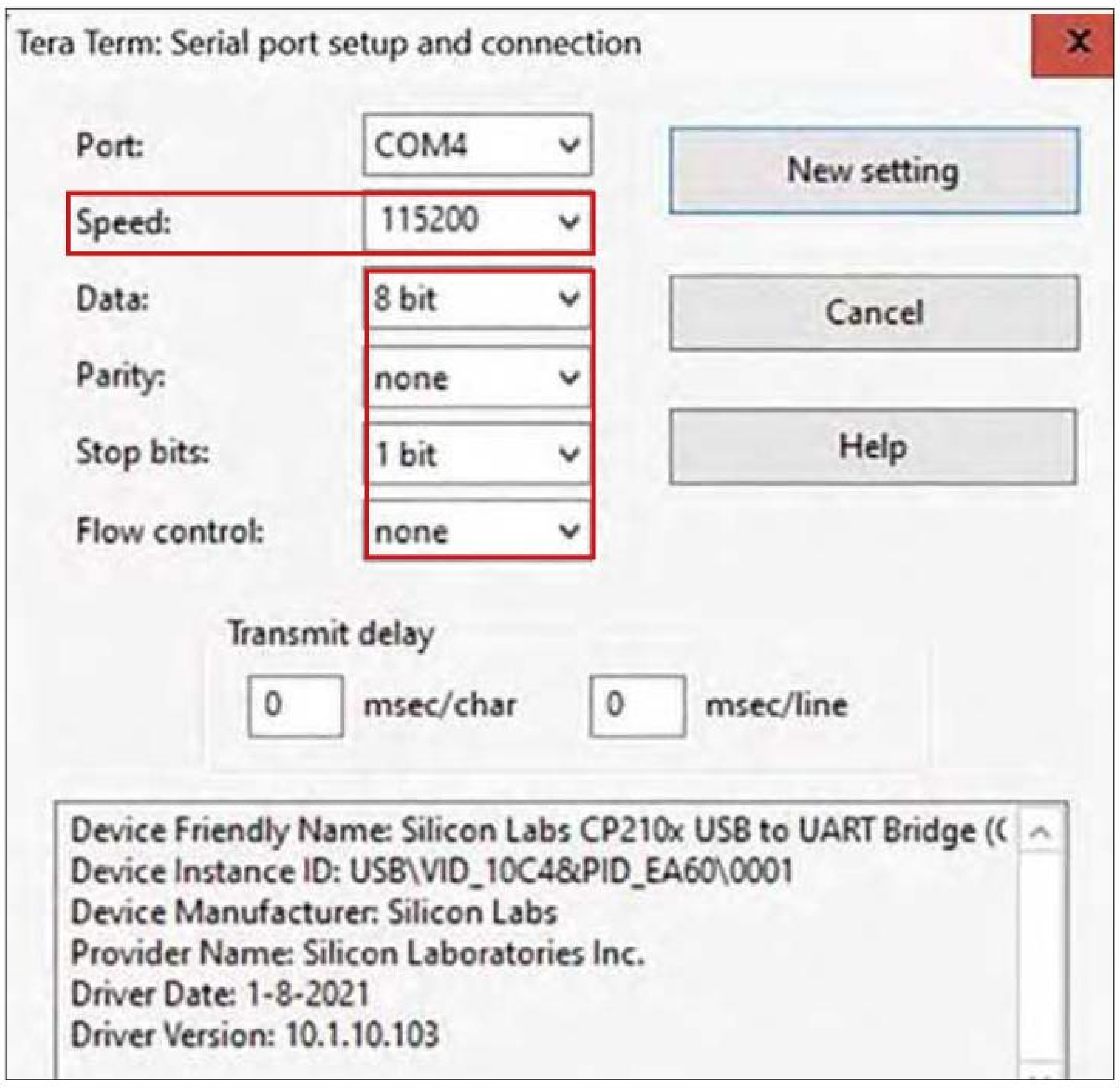


Fig.13. The four connections above put the ESP32 into Normal mode, allowing it to receive AT commands directly from a terminal app such as TeraTerm.

Fig.15. (Right) TeraTerm's Serial port settings need to match those shown here (speed: 115200 baud).



Port: COM4
Speed: 115200
Data: 8 bit
Parity: none
Stop bits: 1 bit
Flow control: none
0 msec/char
0 msec/line

Device Friendly Name: Silicon Labs CP210x USB to UART Bridge (C
Device Instance ID: USB\VID_10C4&PID_EA60\0001
Device Manufacturer: Silicon Labs
Provider Name: Silicon Laboratories Inc.
Driver Date: 1-8-2021
Driver Version: 10.1.10.103

Two common mistakes are an incorrect baudrate (speed) setting (115200), and also the Tx and Rx connections swapped over. Remember, Tx on the USB-to-Serial module goes to Rx on the ESP32 (GPIO16), and Rx on the USB-to-Serial module goes to ESP32 Tx which is GPIO17.

If it still doesn't work, then it is likely to be a power issue. As explained, a 3.3V power supply is required; ideally, capable of supplying a minimum of 250mA. So, if connections and settings are correct but you are still not seeing the `OK` response, then power the ESP32 module from the 3.3V output from the PicoMite (Pin 36).

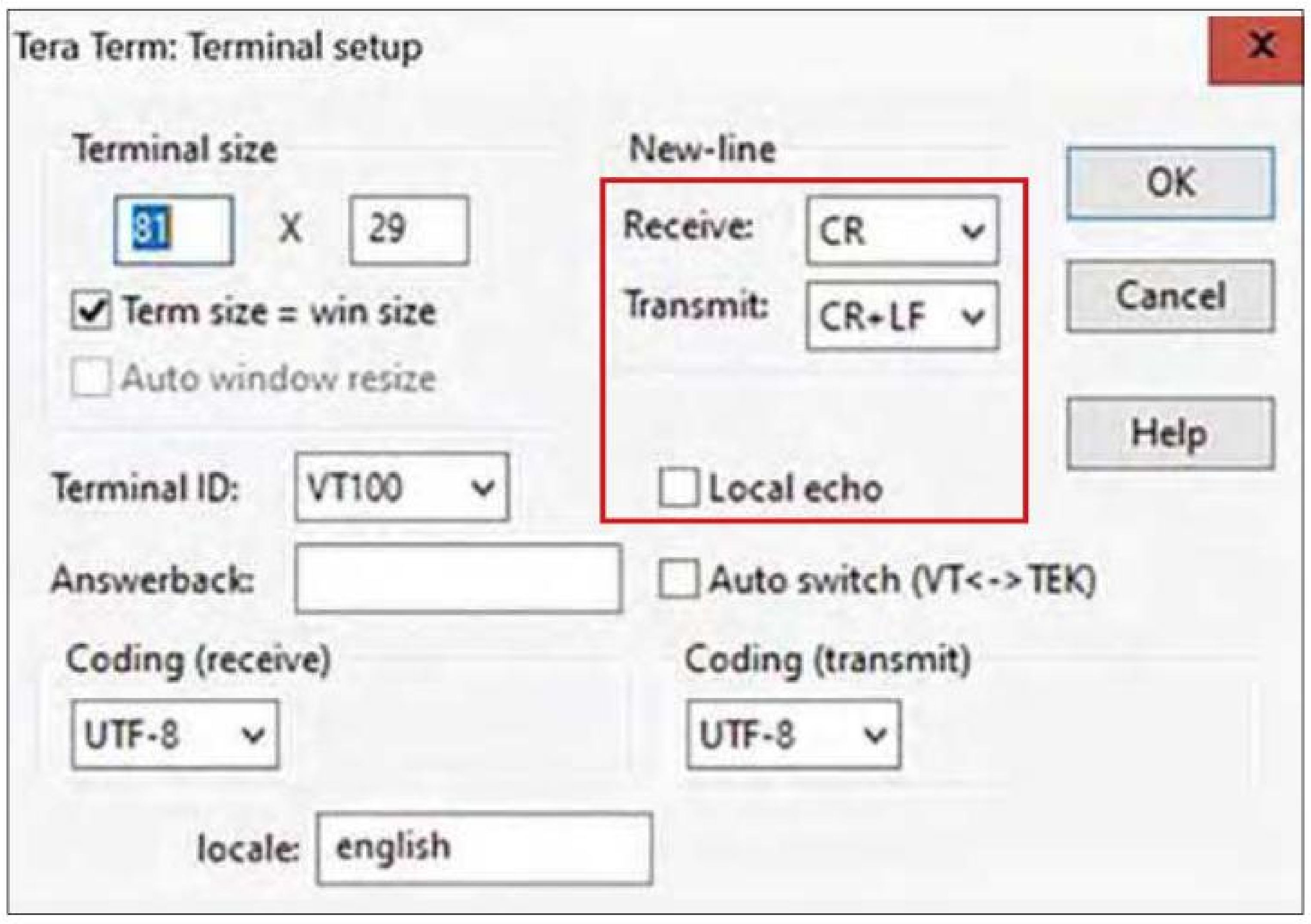
When you've achieved an `OK` response after sending the `AT` command, you can proceed to check that the version of the ESP32 firmware is correct (ie, the firmware update has worked). To do this, type the command `AT+GMR` and it will respond with the version number of the installed firmware (see Fig.16). If all has worked, then you will see something similar to:

```
AT version:2.4.0.0(4c6eb5e - ESP32 - May 20 2022 03:11:58)
SDK version:qa-test-v4.3.3-20220423
compile time(5641e0a):May 20 2022 11:12:05
Bin version:2.4.0(WROOM-32)

OK
```

If you don't see the updated firmware version number, then repeat the upload process. However, if you have followed the above process step-by-step then this is unlikely to be incorrect.

Congratulations, you have successfully updated the ESP32 with the required firmware version in preparation for *Part 2* next month.

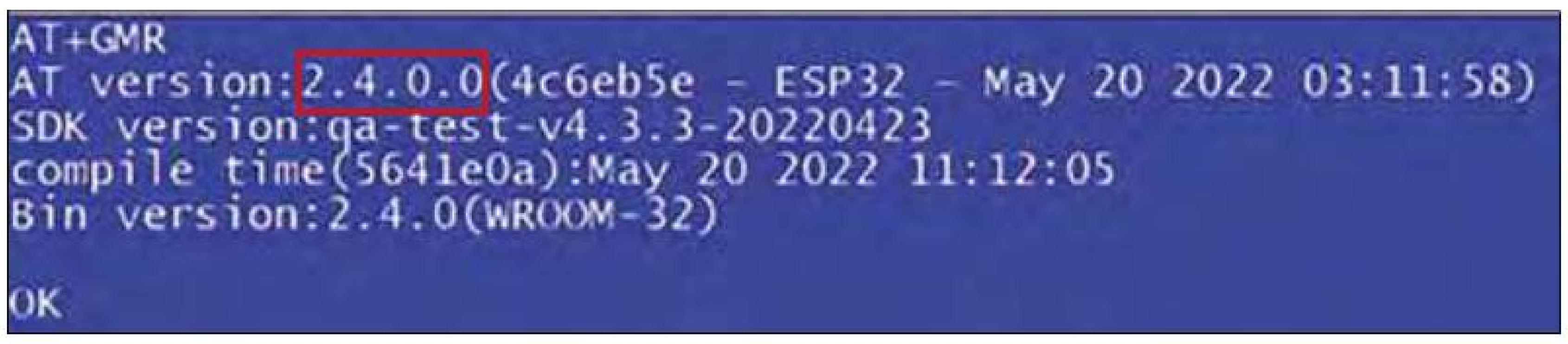


Terminal size
81 X 29
☑ Term size = win size
☐ Auto window resize
New-line
Receive: CR
Transmit: CR+LF
☐ Local echo
Terminal ID: VT100
Answerback:
☐ Auto switch (VT<->TEK)
Coding (receive) UTF-8
Coding (transmit) UTF-8
locale: english

Fig.14. Ensure that the settings in TeraTerm's Terminal settings page match those shown here.

Next time

Next month, we'll configure the Philips Hue Hub and assemble a test circuit – based on a PicoMite and ESP32 – to check we can communicate with the Hue Hub via Wi-Fi. Until then, stay safe, and have FUN!



```
AT+GMR
AT version:2.4.0.0(4c6eb5e - ESP32 - May 20 2022 03:11:58)
SDK version:qa-test-v4.3.3-20220423
compile time(5641e0a):May 20 2022 11:12:05
Bin version:2.4.0(WROOM-32)

OK
```

Fig.16. To test if the ESP32 firmware upload was successful, use the `AT+GMR` command, and check the version number – here, 2.4.0.0.

Questions? Please email Phil at:
contactus@micromite.org

Max's Cool Beans

By Max the Magnificent

Arduino Bootcamp – Part 5

I'm currently ambling around with a bounce in my stride and a great big sloppy grin slapped on my face. I just received an email that brought a flush to my cheeks (my face went red as well). The reason for my jaunty jocularity is that the communication in question came from Mike Cowlishaw, who is a visiting professor at the Department of Computer Science at the University of Warwick, a Fellow of the Royal Academy of Engineering, and a retired IBM Fellow, to name but a few of Cowlishaw's cornucopia of credentials. Suffice it to say that Mike is something of a legend in certain circles (possibly triangles and squares too) – see: **https://bit.ly/400Br8x**

In his communique, Mike spake as follows: 'Hi Max, as usual, I thoroughly enjoyed your article in the April 2023 *PE*. Especially so because decimal representations and arithmetic are dear to my heart. I've been working on them, off and on, since 1981. I found out in 2001 that there was no standard way of doing decimal arithmetic. Different software and hardware could give different results for a multiply on the same arguments (even within the same company). However, I was able to fix that, and decimal arithmetic is now in the IEEE 754 standard for floating-point arithmetic, as well as in hardware. Here are a couple of references you might find interesting: *Decimal Floating-Point: Algorism for Computers* (some history and rationale, **https://bit.ly/3JzMOz6**), *A Summary of Densely Packed Decimal encoding* (DPD) – more efficient than 8421 BCD; now implemented in hardware and software, **https://bit.ly/3l3V1lq** – and lots more at: **https://bit.ly/3JaZwCF** '

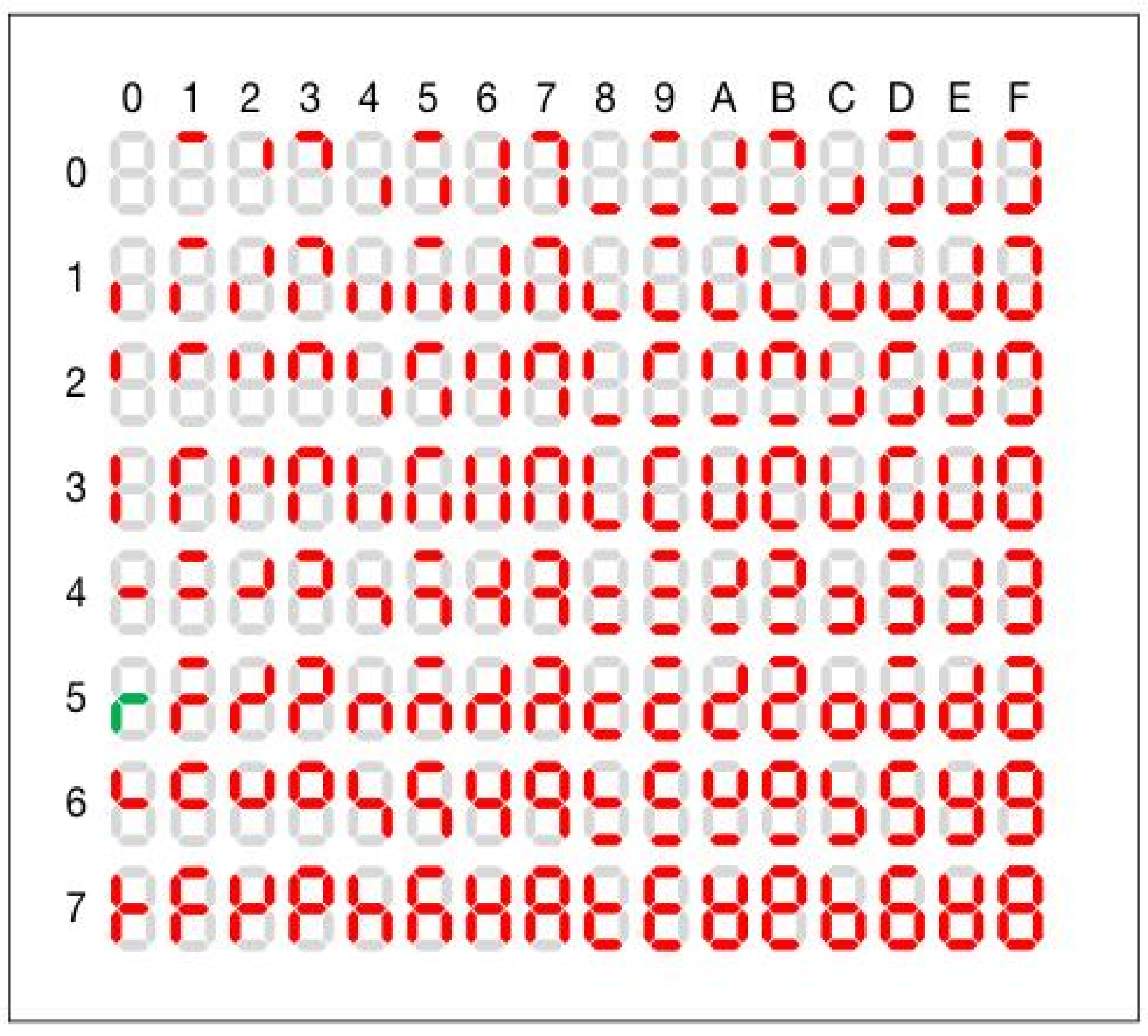


Fig.1. 16×8 grid showing the 128 possible states for a 7-segment display.

OH NO!

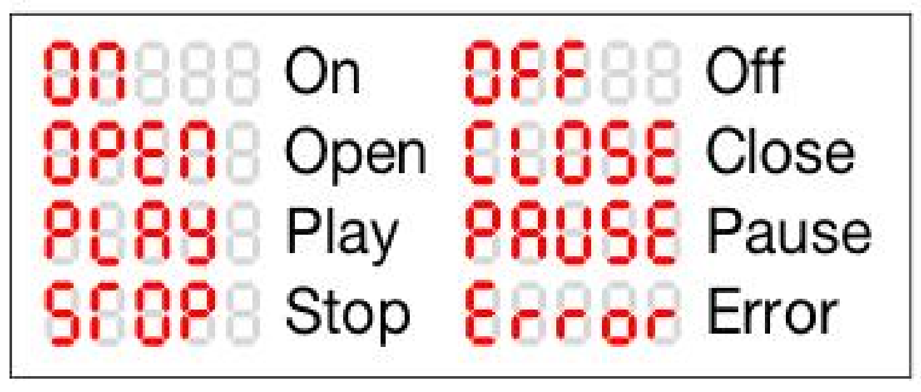
Toward the end of my previous column (*PE*, April 2023), we noted that – since we can individually control the segments on our 7-segment display – we can use them to represent characters other than the numerals 0 through 9. As an example, we took the current latest and greatest version of our program, which repeatedly counts and displays the values 0 through 9, and we modified it to commence by first bidding us a cheery, 'HELLO.'

We're going to use this version of the program as the starting point for this month's experiments. Just to ensure we're all tap-dancing to the same skirl of the bagpipes; you can download a copy of our current breadboard layout (file **CB-May23-01.pdf**) along with the latest version of our program (file **CB-May23-02.txt**). As usual, all the files mentioned in this column are available from the May 2023 page of the *PE* website at: **https://bit.ly/pe-downloads**

Paste the program into your Arduino's integrated development environment (IDE) and then save it with a name of your choosing along the lines of: **Auto_Dec_Count_Up**

We closed the aforementioned column by asking you to try to think of other characters and symbols and messages we could create. Since we have seven segments (excluding the decimal point), and since each segment can be in one of two states (on and off), this means we have $2^7 = 128$ different possibilities. The best way to start is to enumerate these possibilities using a sort of graphical binary count, as illustrated in Fig.1.

Fig.2. Example 7-segment messages



There are two questions you should be asking about Fig.1. First, why reference the six right-hand columns using the letters 'A' through 'F' rather than the numbers 10 through 15. Second, why highlight (in green) the two segments associated with the character in row 5, column 0.

There are two answers with respect to the first question: (a) This figure looks crowded if we use the numbers 10 through 15 and (b) this leads us into the topic of hexadecimal numbers, which is introduced later in this column.

In the case of the second question, I highlighted these two little rascals to illustrate the fact that some of our segment combinations may not appear to have any meaning when considered in isolation, but their significance becomes apparent when viewed in the context of other combinations. For example, these two segments are immediately apparent as representing a lowercase 'r' when seen in the context of the 'Error' message shown in Fig.2.

Tick tock

Although this is a bit of a (short) diversion, the topic of controlling individual segments on 7-segment displays just reminded me of the awesome project created by EE Student Frugha, as documented on **Hackaday.io** – see: **https://bit.ly/3JxO8lS**

This little rascal (the project in Fig.3, not Frugha) involves a 6-row x 12-column

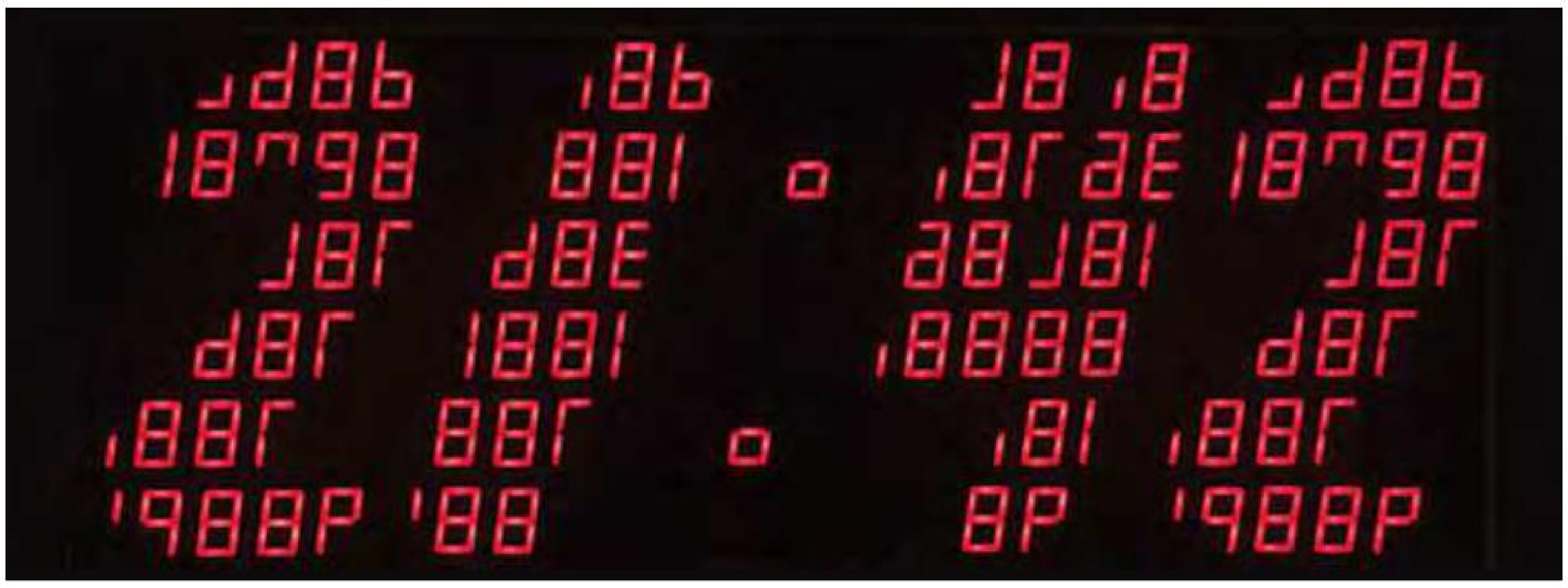


Fig.3. One thing to do if you find yourself with 144 7-segment displays (Source: Frugha)

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= 144 element array of 7-segment displays. Observe how some of the displays are presenting only fragments of characters. In addition to being employed as a clock, this bodacious beauty can also be used to display all sorts of other data and imagery.

Hexactly

Previously, we noted that groupings of four binary digits, or 'bits', are common. Such a grouping is known as a 'nybble' (or 'nybl' or 'nibble'). Since four bits can represent $2^4 = 2 \times 2 \times 2 \times 2 = 16$ different combinations of 0s and 1s, we can use a nybble to encode (map) our ten decimal values as BCD. But this involves our employing only ten of the binary patterns, 0000 through 1001, leaving the remaining six patterns 1010 through 1111 unused and unloved (Fig.4a).

Most of the time (ie, when we aren't working in BCD), we prefer to take full advantage of all 16 binary patterns, 0000 through 1111, that are available in a nybble (Fig.4b). Although we can certainly consider these values in terms of their decimal equivalents (0 through 15), this quickly becomes clunky when we wish to work with multi-nybble values.

Suppose we are working with a 4-nybble (16-bit) value, for example. If we consider this field to be in BCD format, we can use it to represent values between 0 and 9999. By comparison, if we consider it to be a standard binary field, it can support $2^{16} = 65{,}536$ different combinations of 0s and 1s, which we can use to represent unsigned (positive) values between 0 and 65,535.

Unfortunately, large binary values typically don't make much sense when we first see them. As an example, consider the 16-bit binary value 1010 0101 1110 1001 (the spaces have no meaning other than indicating that this is a 4-nybble value). This equates to 42,473 in decimal, but the mapping between the binary and decimal domains is not intuitively obvious.

An alternative is to turn to the hexadecimal (base-16) number system. This requires us to assign unique symbols to each of the sixteen binary combinations supported by the nybble. We already have the 0 through 9 characters at our disposal, so we need only six more. Instead of inventing six completely new symbols – which would be a pain because (a) we would have to memorise them and (b) they wouldn't exist on our computer keyboards – mathematicians and computer scientists decided to employ the letters A through F.

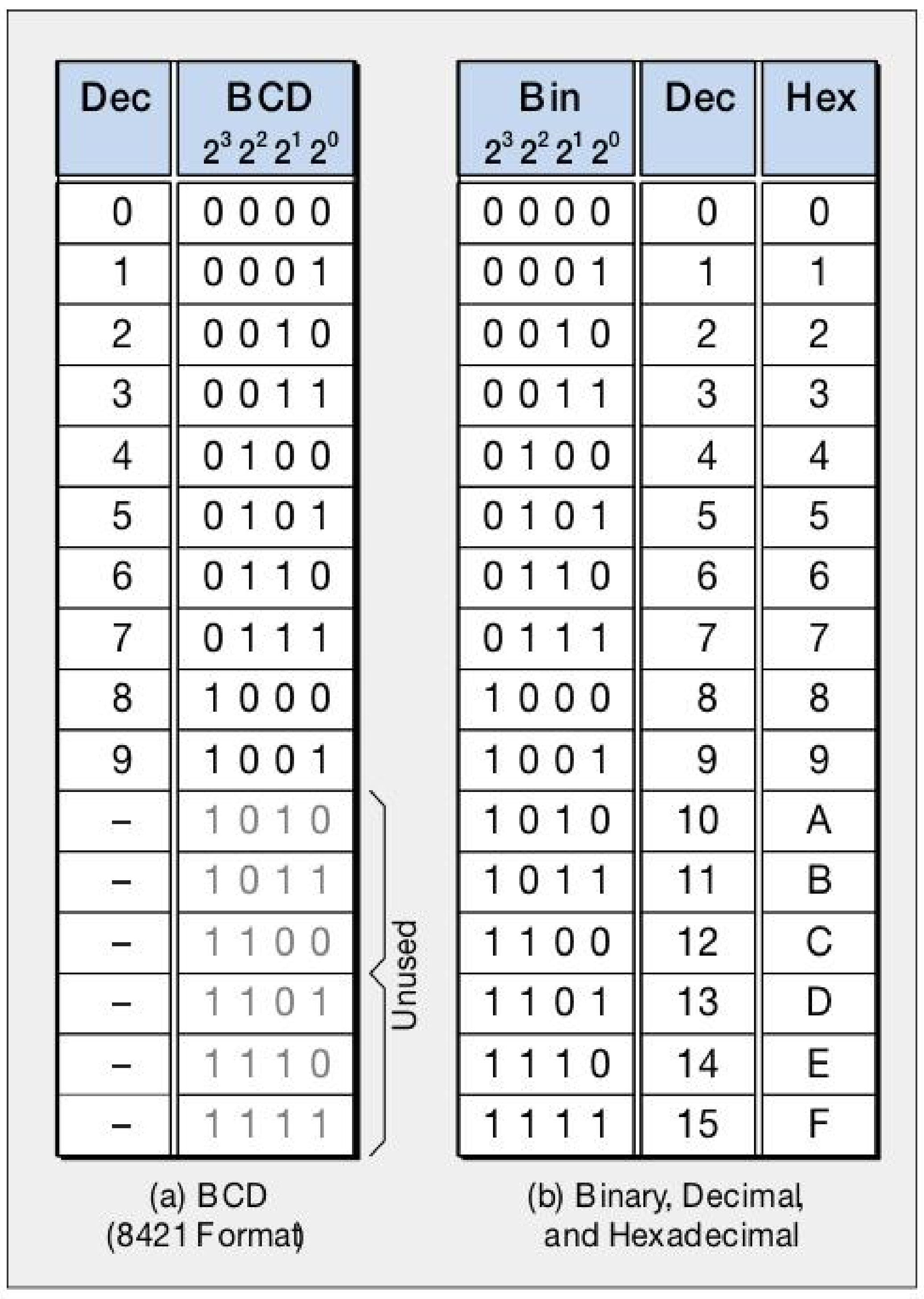
Now let's return to our previous 4-nybble example of 1010 0101 1110 1001. If we wish to transpose this into hexadecimal, all we need do is perform a one-for-one transformation between the four binary nybbles and their corresponding hexadecimal digits: 1010 = A, 0101 = 5, 1110 = E, and 1001 = 9. This means 1010 0101 1110 1001 in binary is the same as A5E9 in hexadecimal.

Obviously, it's just as easy to go in the other direction (we would be in a bit of a pickle were this not the case). If we start with a hexadecimal value of A5E9, then from Fig.4b we know that A = 1010, 5 = 0101, E = 1110, and 9 = 1001, so A5E9 in hexadecimal is the same as 1010 0101 1110 1001 in binary.

As we've previously discussed, starting with the least-significant (rightmost) digit, column weights in binary (base-2) are $2^0 = 1$, $2^1 = 2$, $2^2 = 4$, $2^3 = 8$… and so on. By comparison, column weights in decimal (base-10) are $10^0 = 1$, $10^1 = 10$, $10^2 = 100$, $10^3 = 1000$… Thus, it should come as no surprise that the column weights in hexadecimal (base-16) are $16^0 = 1$, $16^1 = 16$, $16^2 = 256$, $16^3 = 4096$ and so on.

Just for giggles and grins, let's suppose we wish to convert our A5E9 hexadecimal value into decimal. As with any other place value number system, each digit forming the number is multiplied by its column's weight and the results are summed to give the total value of that number. In this case, we have $(A \times 16^3) + (5 \times 16^2) + (E \times 16^1) + (9 \times 16^0)$, which is the same as $(A \times 4096) + (5 \times 256) + (E \times 16) + (9 \times 1)$, which is the same as $(10 \times 4096) + (5 \times 256) + (14 \times 16) + (9 \times 1)$, which equals 42,473 in decimal (phew!).

Last, but not least, when indicating hexadecimal values in the C/C++ programming languages, we prefix them with 0x or 0X (I prefer the former), for example, `0xA5E9`. Also, we can use lowercase letters if we wish, `0xa5e9`, but I favour the uppercase approach.



Dec	BCD $2^3\,2^2\,2^1\,2^0$
0	0 0 0 0
1	0 0 0 1
2	0 0 1 0
3	0 0 1 1
4	0 1 0 0
5	0 1 0 1
6	0 1 1 0
7	0 1 1 1
8	1 0 0 0
9	1 0 0 1
–	1 0 1 0
–	1 0 1 1
–	1 1 0 0
–	1 1 0 1
–	1 1 1 0
–	1 1 1 1

Unused

(a) BCD (8421 Format)

Bin $2^3\,2^2\,2^1\,2^0$	Dec	Hex
0 0 0 0	0	0
0 0 0 1	1	1
0 0 1 0	2	2
0 0 1 1	3	3
0 1 0 0	4	4
0 1 0 1	5	5
0 1 1 0	6	6
0 1 1 1	7	7
1 0 0 0	8	8
1 0 0 1	9	9
1 0 1 0	10	A
1 0 1 1	11	B
1 1 0 0	12	C
1 1 0 1	13	D
1 1 1 0	14	E
1 1 1 1	15	F

(b) Binary, Decimal, and Hexadecimal

Fig.4. Introducing hexadecimal.

What? More characters?

In our previous column, we decided which segments we were going to use to represent the decimal digits 0 through 9 on our 7-segment display (Fig.5).

If we wish to display hexadecimal values on our 7-segment display, we are going to have to return to the drawing board to decide which segments we can use to represent the characters A through F. Sad to relate, although we can easily create uppercase representations of A, C, E, and F, we are obliged to make do with lowercase incarnations of 'b' and 'd' (Fig.6). The reason is simple: upper-case 'B' looks just like '8' and upper-case 'D' could be mistaken for '0' (zero).

Furthermore, this explains why we use segment A in our representation of the number 6 because not using this segment in the letter 'b' allows us to differentiate between these two characters.

Fire up the IDE!

If you haven't already done so, use the Arduino IDE to open our **Auto_Dec_Count_Up** program (or 'sketch' in the vernacular of the Arduino fraternity) and save it out as: **Auto_Hex_Count_Up**.

Now, all we need to do is modify this program from repeatedly counting from 0 to 9 in decimal to repeatedly counting from 0 to F in hexadecimal.

You've gone pale. What's the problem? This really is easy peasy lemon squeezy because it involves only two small tweaks. First, we change our definition of `NUM_DIGITS` from 10 to 16. Second, we modify our `DigitSegs[]` array to include the definitions of the segments used to represent the A through F characters, as illustrated in Listing 1.

If you have any problems, you can download my version (file **CB-May23-03.txt**). Use the Sketch > Verify/Compile command to make our new program compile without errors, and then use the Sketch > Upload command to load the program into your Arduino and run it. Following the 'HELLO' message, you will (hopefully) see your 7-segment display repeatedly counting from 0 to F in hexadecimal.

Switch it up!

For our next experiment, rather than let our program count automatically, we're going to control things by hand using a momentary pushbutton switch. The 'momentary' portion of this appellation means this is a non-latching switch that causes a temporary change in the state

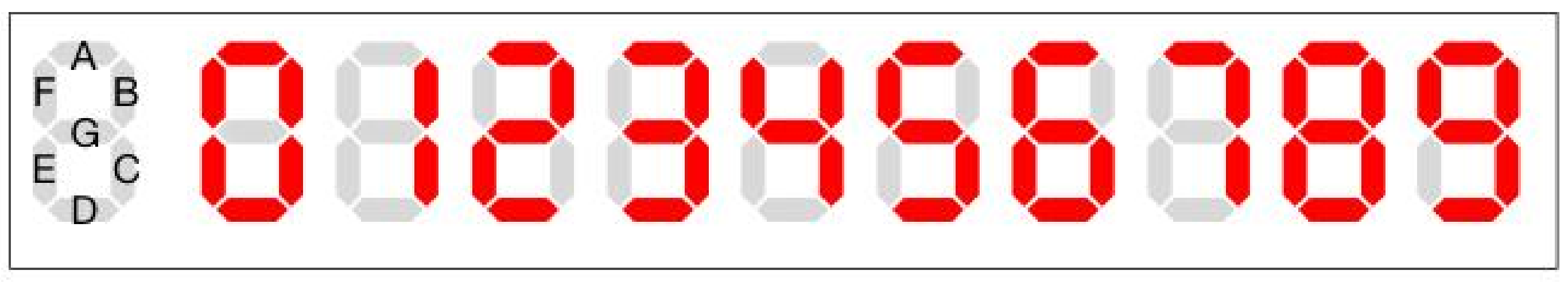


Fig.5. Segments used to represent 0 through 9.

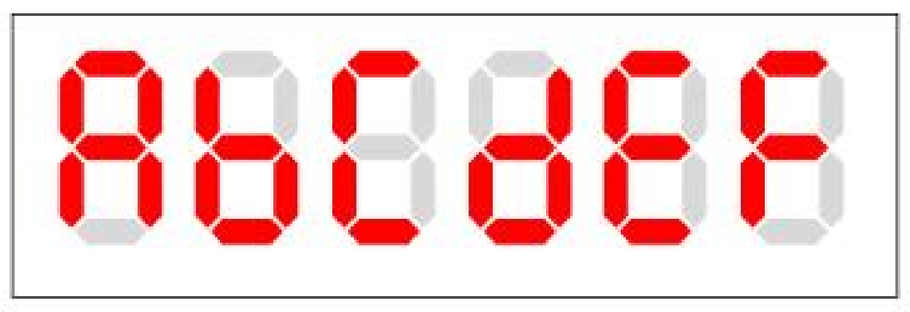
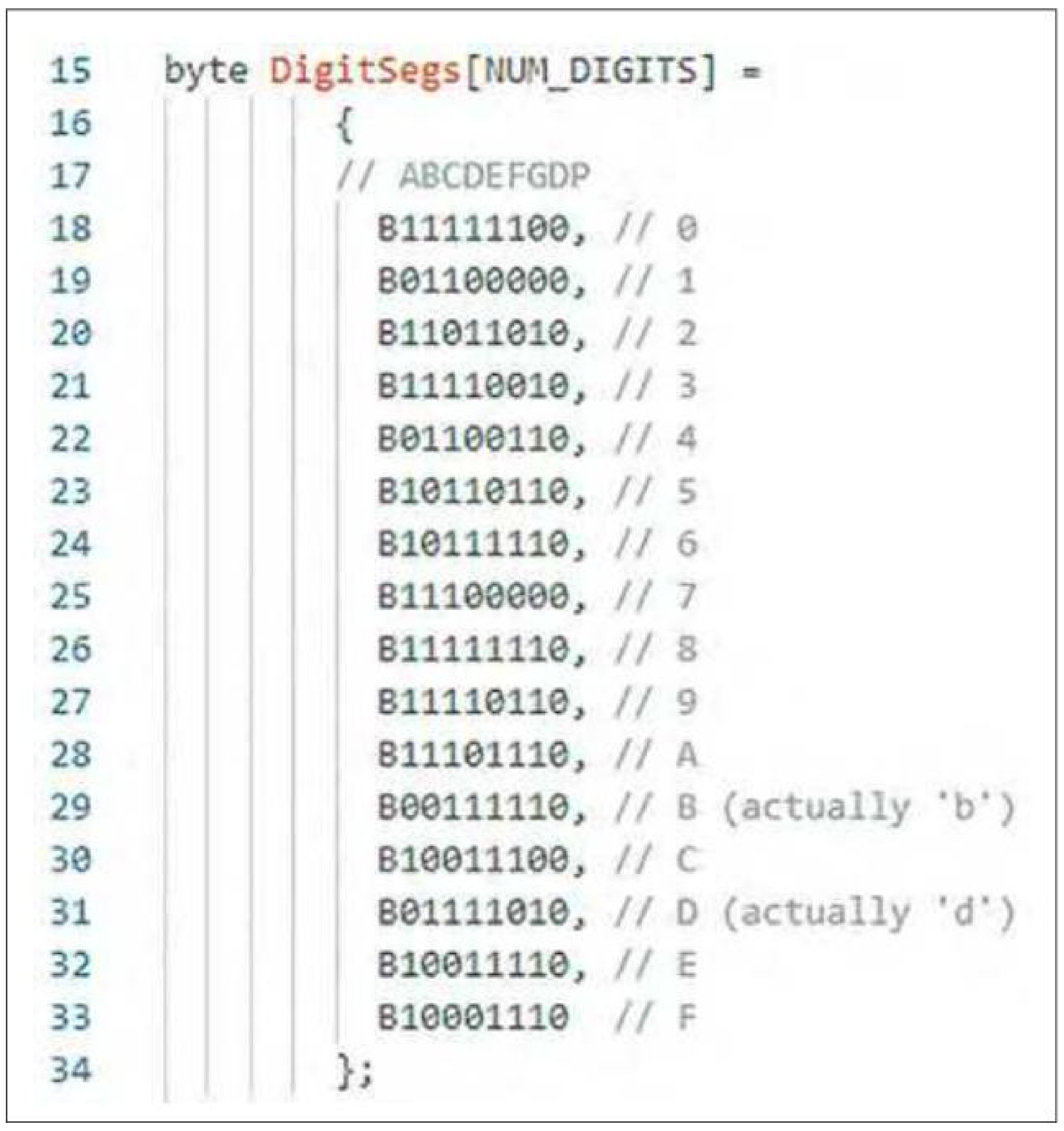


Fig.6. 7-segment A through F.



```
byte DigitSegs[NUM_DIGITS] =
     {
     // ABCDEFGDP
       B11111100, // 0
       B01100000, // 1
       B11011010, // 2
       B11110010, // 3
       B01100110, // 4
       B10110110, // 5
       B10111110, // 6
       B11100000, // 7
       B11111110, // 8
       B11110110, // 9
       B11101110, // A
       B00111110, // B (actually 'b')
       B10011100, // C
       B01111010, // D (actually 'd')
       B10011110, // E
       B10001110  // F
     };
```

Listing 1. Modifying our `DigitSegs[]` array.

of the circuit only while the switch is activated (pressed).

These switches are available in 2-pin or 4-pin packages. Both types are 6mm square. Also, both are single-pole, single-throw (SPST) devices with normally open (NO) contacts, which means pressing the switch closes the contact and makes the connection.

Either type of switch will do, but I favor the 2-pin versions for our breadboard-based application. I purchased a pack of 20 for only $5.99 here in the US (**https://amzn.to/3JG781t**). The closest equivalent I could find in the UK was a pack of 20 switches for £3.99 (**https://amzn.to/3Tk7Q87**). For some reason, the UK versions have longer (14.5mm) leads, so you should cut these down to a suitable length for use in your breadboard.

Thus far, we've been using the Arduino's digital input/output (I/O) pins D0 through D14. The Arduino Uno also has six analogue input pins, A0 through A6. Happily, these analogue pins can also act as digital pins if we wish, so let's add one of our switches along with a pull-up resistor to our breadboard and connect things up as shown in Fig.7. An image of the entire breadboard showing this switch and the 7-segment display is available in the download file **CB-May23-04.pdf**.

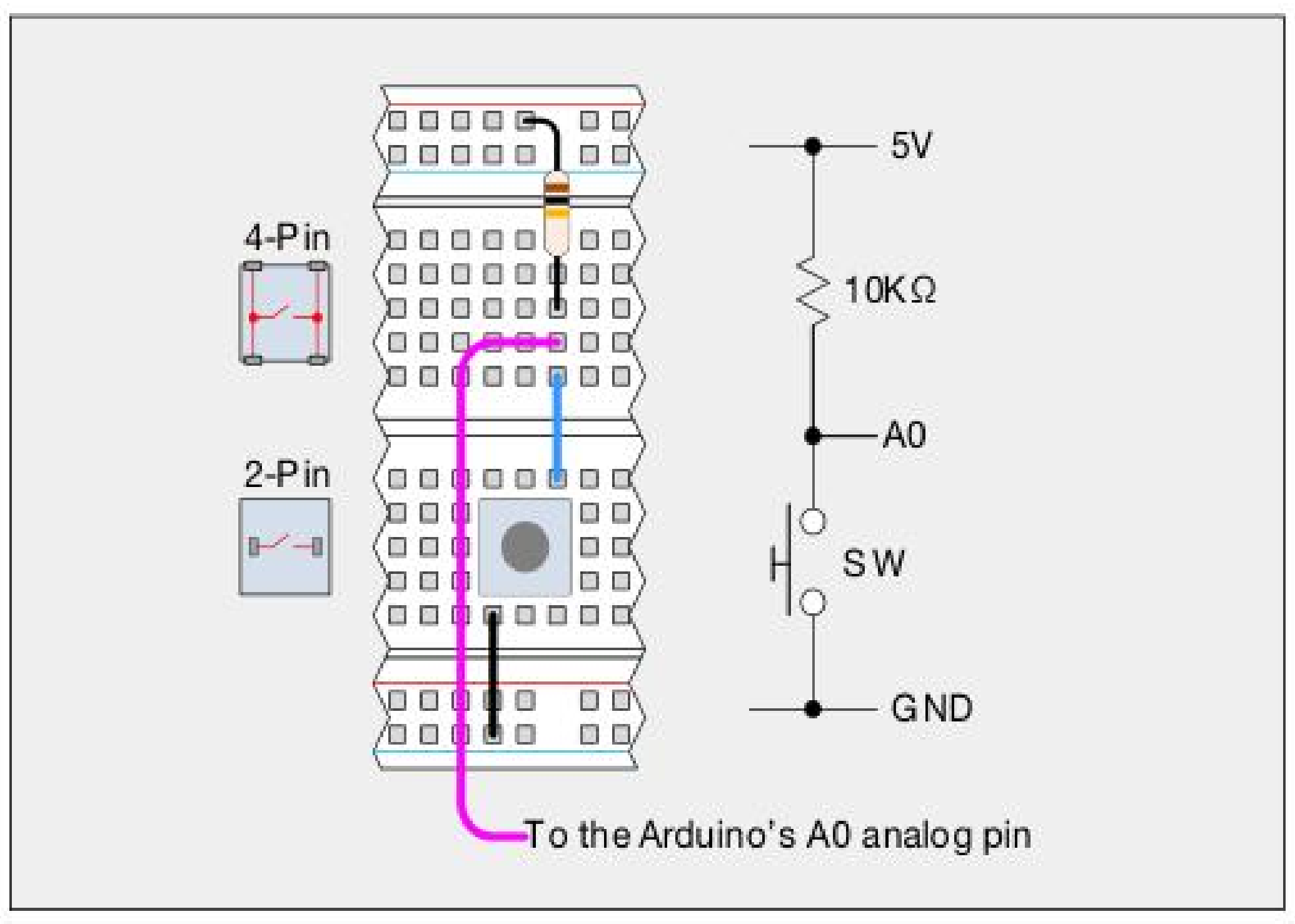


Fig.7. Adding a switch and pull-up resistor.

Assuming you are using the 2-pin version of the switch, make sure the pins are presented as shown in Fig 7. Pressing the switch will make the connection between the black wire (connecting the left-hand side of the switch to 0V) and the blue wire (connecting the right-hand side of the switch to the 'south' side of the resistor). It's important to get the orientation of the switch correct. If you rotate it by 90°, the black and blue wires will remain forever unconnected no matter how enthusiastically you press the button.

If you end up using the 4-pin version of this switch, you'll find the pins have a bit of a kink and you will have to straighten them out using a pair of pliers. In this case, the pins are connected in pairs as illustrated in Fig.7 (use a multimeter to determine which pins are connected if you're not sure). Once again, it's important to get the orientation of the switch correct. If you rotate it by 90°, the result will be to permanently connect the south side of the resistor to the ground rail. This won't do any damage, but the circuit will behave as though you are constantly pressing the switch.

In the schematic (circuit) diagram portion of Fig.7, we've used A0 to indicate the wire/signal feeding the Arduino's A0 input. When the switch is open (inactive/not pressed), we employ a pull-up resistor to pull A0 up to 5V (logic 1 or `HIGH`). We can use any value between 1kΩ and 10kΩ (or higher) for this resistor. Personally, I usually use 10kΩ values with their brown-black-orange bands for my pull-up and pull-down resistors. When the switch is closed (active/pressed), it connects the A0 signal to 0V (logic 0 or `LOW`).

Once you've wired everything up, STOP! This is the perfect time to slow down, take a deep breath, and check that everything is as it should be. Even though there are only two components and three wires in this circuit, you'd be amazed how easy it is to do something silly, such as plugging the north end of the resistor into the 0V (ground/blue) rail rather than the 5V (power/red) rail, for example. (No, I certainly did not just do this myself. Why do you ask?)

I recommend re-drawing the circuit on paper, and then going through it component-by-component and connection-by-connection using a colored pencil or a highlighter to mark things on the diagram as you verify them on the breadboard.

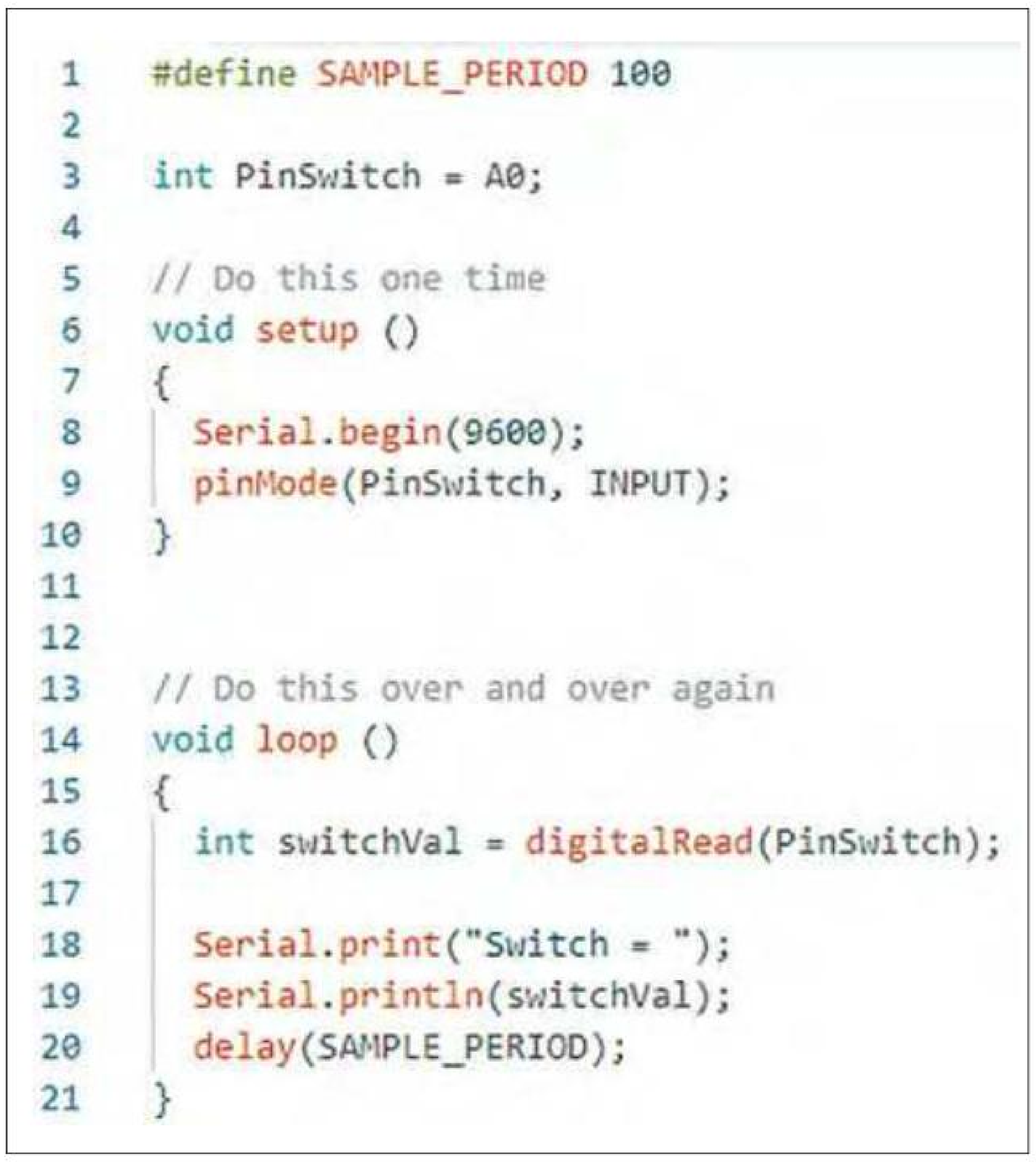
Testing… testing…

Remember, we can make our lives a whole lot easier if we take an 'atomic' view of the world and test things in isolation before we use them as part of a larger function or system. In this case, we will start by writing a simple program that reads the value of the switch and displays that value on our computer screen. Let's call this program something like **Switch_Test_01**. My version of this program is shown in Listing 2 (file **CB-May23-05.txt**).

We start by defining a constant called `SAMPLE_PERIOD` and setting this to 100. Later, when we use this value in a `delay()` function, it will be interpreted as 100ms (milliseconds), which means we will be reading (sampling) the state of our switch every tenth of a second.

Next, we declare an integer variable called `PinSwitch` and assign it a value of `A0`. In the real world, pin numbers depend on what type of processor we are using. That's why we inform the IDE of the processor type, which is the Arduino Uno in our case. This allows the IDE to automatically replace the `A0` value with the appropriate pin number when we compile the program.

As we see, the `setup()` function contains only two statements. Let's discuss these in reverse order. We use the in-built `pinMode()` function to inform the Arduino if we want its digital pins to act as inputs or outputs. In earlier programs, we've set the pins driving our 7-segment display to be of type `OUTPUT`. In this case, we are telling the Arduino that we want the pin connected to our switch to be of type `INPUT`. If the truth be told, this is somewhat redundant because – when it's



```
#define SAMPLE_PERIOD 100

int PinSwitch = A0;

// Do this one time
void setup ()
{
  Serial.begin(9600);
  pinMode(PinSwitch, INPUT);
}


// Do this over and over again
void loop ()
{
  int switchVal = digitalRead(PinSwitch);

  Serial.print("Switch = ");
  Serial.println(switchVal);
  delay(SAMPLE_PERIOD);
}
```

Listing 2. First switch test program.

powered-up – the Arduino will set all its pins to be inputs by default. However, defining this explicitly makes the program easier to read, so we do it anyway.

Now let's return to the first statement in our `setup()` function. The Arduino has a serial communications capability that allows it to talk to something called the 'Serial Monitor' on the host computer. Sometimes we may wish to use the Serial Monitor to send commands and data to the Arduino. In this case, however, we are going to use the Arduino to transmit information to be displayed on the Serial Monitor. The `Serial.begin()` statement tells the Arduino to get ready to exchange messages with the Serial Monitor. The argument of `9600` is commonly called the bit rate or the baud rate. This tells the Arduino we wish to use a data rate of 9600 bits per second (bps), which is the default used by the Serial Monitor (we could set this to be much higher if we wished).

In the case of the `loop()` function, we start by declaring an integer variable named `switchVal` to which we assign the value returned when we call the built-in function `digitalRead()` to access the current state of our switch. As we've previously discussed, we can think of the values we read on our digital inputs as `LOW` (0V) or `HIGH` (5V), but the Arduino will see them in terms of 0 and 1, respectively.

The `Serial.print()` statement prints whatever argument it is presented with. In this case, we are asking it to print the string 'Switch = '. This will leave the cursor on the same line on the screen, which means we can use multiple instantiations of this statement to build multi-element lines on the display.

Similarly, the `Serial.println()` statement will also print whatever argument it is presented with. In this case, we are asking it to print the value we read from our switch and loaded into our `switchVal` variable. However, this statement will also throw a new line character when it's done, which will move the cursor to the next line on the display.

Finally, we use the built-in `delay()` function to pause for `SAMPLE_PERIOD` (100 milliseconds), and then do the whole thing again.

Upload this program into your Arduino and then use the Tools > Serial Monitor command to launch the Serial Monitor (or click the icon that looks like a magnifying glass with a dot in the center located in the upper right-hand corner of the IDE).

After a second or so, you should see a never-ending series of the following lines of text start to appear in your Serial Monitor window:

```
Switch = 1
Switch = 1
Switch = 1
   :
```

If you see 0s instead of 1s, the first thing to check is that the north end of your resistor is connected to the 5V (red) rail and not the 0V (blue) rail by mistake. If you are using a 4-pin switch, the second thing to check is that it's in the correct orientation (try rotating it clockwise by 90°).

Once you start seeing the 1s, try pressing and holding the pushbutton, which should result in you seeing the following lines of text appear in your Serial Monitor window:

```
Switch = 0
Switch = 0
Switch = 0
   :
```

Assuming you do see these 0s, play around by pressing and releasing the switch until your excitement is sated. However, if you continue to see 1s rather than 0s, the first thing to check is that the south side of your black wire is connected to the 0V (blue) rail and not the 5V (red) rail. If you are using a 2-pin switch, the second thing to check is that it's in the correct orientation (try rotating it anticlockwise by 90°).

Feeling bold?

If you're feeling bold, what I'd like you to do is return to our **Auto_Dec_Count_Up** program and save this as **Switch_Test_02**.

Your mission, should you decide to accept it, is to use the minimum number of modifications necessary to tweak this program so that, after bidding us 'HELLO,' it loops around reading the state of the switch and displaying corresponding 0 and 1 values on the 7-segment display.

Bolder still??

A second task I would be delighted for you to perform would be to return to our **Auto_Dec_Count_Up** program and save this as **Switch_Dec_Count_Up**.

In this case, following the 'HELLO' message, we want to commence by presenting a 0 on the display. Next, we want the program to loop around checking the state of the switch. Whenever the switch is pressed, we want to increment (add 1 to) the value on the display. As usual, when we reach 9, pressing the button one more time will cause the display to wrap around back to 0.

Serial functionality

Much like the built-in functions `pinMode()`, `digitalRead()`, `digitalWrite()`, `delay()` and `random()`, the serial communications functionality presented here isn't part of the C/C++ languages. In this case, it's a library that's been written in C++ and that's automatically included in the Arduino's IDE.

Since this library is written in C++, the `Serial` portion of these statements is classed as being an 'object,' while the `.begin()`, `.print()` or `.println()` portions of the statements are officially referred to as 'methods' (supported operations of the object). Methods may also be referred to as 'functions.'

More information about serial functionality is available in the reference section of the **Arduino.cc** website: **https://bit.ly/2qOGWbo**

Yet bolder???

Wow! I have to say that I'm thrilled by your enthusiasm. In the case of this third undertaking, I want you to start by adding a second pushbutton switch (with associated pull-up resistor) to your breadboard and connect the output from this switch to pin A1 on your Arduino.

Next, I want you to take the current version of your **Switch_Dec_Count_Up** program and save it as **Switch_Dec_Count_Up_and_Down**. Modify this new incarnation of the program such that pressing the original switch causes the display to increment, while pressing the new switch causes it to decrement. In this case, if the display is currently at 0, then pressing the decrement button should cause it to wrap around back to 9.

All of this should keep you busy for a while. I'll present my versions of these programs in my next column. In the meantime, as always, I welcome your insightful comments, perspicacious questions, and sagacious suggestions.

Components from Part 1

LEDs (assorted colours)	**https://amzn.to/3E7VAQE**
Resistors (assorted values)	**https://amzn.to/3O4RvBt**
Solderless breadboard	**https://amzn.to/3O2L3e8**
Multicore jumper wires (male-male)	**https://amzn.to/3O4hnxk**

Components from Part 2

7-segment display(s)	**https://amzn.to/3Afm8yu**

Components for Part 5

Momentary pushbutton switches	**https://amzn.to/3Tk7Q87**

Cool bean Max Maxfield (Hawaiian shirt, on the right) is emperor of all he surveys at **CliveMaxfield.com** – the go-to site for the latest and greatest in technological geekdom.

Comments or questions? Email Max at: **max@CliveMaxfield.com**

Circuit Surgery

Regular clinic by Ian Bell

Op amps as comparators

GAP/R
MODEL
K2-W
uA741C
7224

Op amp evolution: (top) GAP/R K2-W: a vacuum-tube op amp from 1953; (below) uA741 IC op amp, first produced in 1967. (Images: Wikipedia)

An EEWeb forum post by user Maddan417 describes problems with a voltage comparator circuit using the LM741 op amp (see Fig.1), which does not operate as hoped. The circuit needs to switch at 1.2V for inputs ranging from 1V to 3.5V, but switches at 2.5V. Maddan417 is attempting to do this using an LM741 op amp, L7805 voltage regulators, a voltage divider, and a transistor. The 741 is supplied from a single 5V rail from the regulator, with the power source being an automotive alternator. Maddan417's problems also included the op amp output not being 0V when the circuit has switched to a 'low' output state.

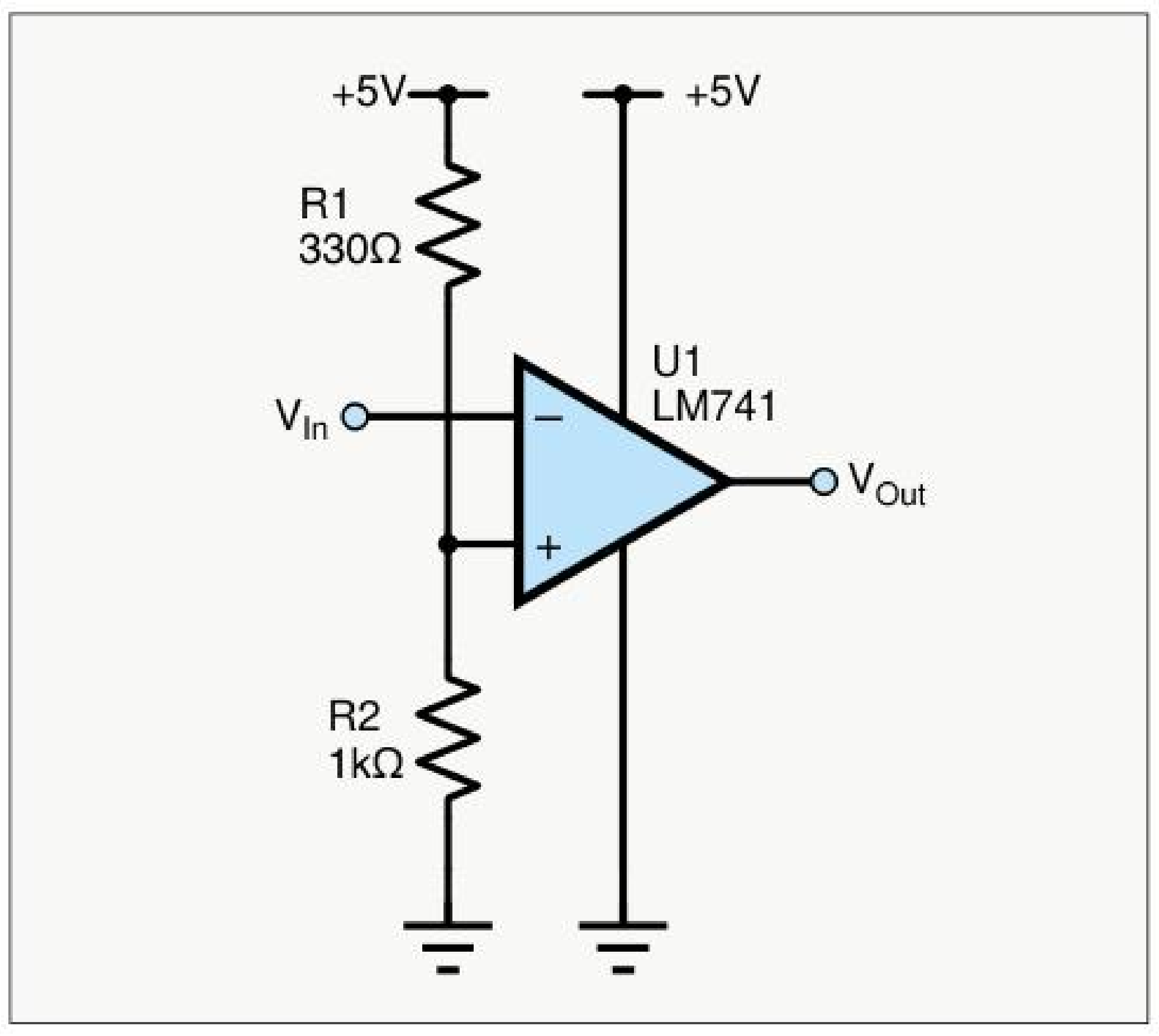


Fig.1. Maddan417's circuit.

Another contributor pointed out that the incorrect switching voltage is at least partly due to swapped or incorrectly calculated values for the resistors used to set the switching point. The values shown set the comparator threshold to $5 \times 1\text{k}\Omega/(1\text{k}\Omega + 330\Omega) = 3.76\text{V}$, swapped they give $5 \times 330\Omega/(1\text{k}\Omega + 330\Omega) = 1.24\text{V}$. The design used two regulators for the supply and potential divider, which is not necessary.

The more fundamental problems are related to the use of the 741 – it is an op amp, not a comparator, its performance is poor, and it is used outside its recommended operating conditions in Maddan417's circuit. In this article we will discuss use of the 741, and op amps in general, as comparators.

The 741

The 741 is a very old op amp – the uA741 was designed by Dave Fullagar of Fairchild in 1968. At the time, there were very few other op amps on the market. The 741 was preceded by the uA702 in 1963 and uA709 in 1965, also both from Fairchild. The uA702 was the first monolithic (single chip) IC op amp, previously op amps were modular solid-state devices using discrete transistors, or hybrid circuits using chip transistors, or combination of ICs and discrete components. Before that there were valve / vacuum tube op amps. If you would like a long, detailed read on op amp history try *Chapter H: Op Amp History* by Walt Jung from the *Op Amp Applications Handbook*, 2005 – see: **https://bit.ly/pe-may23-op1**

Robert Widlar, the designer of the uA702 and uA709, moved to National Semiconductor and produced the LM101, which, like the LM741 is still in production. Dave Fullagar improved on the LM101 to produce the uA741, which quickly became very popular. As part of IEEE Spectrum's 'Chip Hall of Fame' series of articles – **https://bit.ly/pe-may23-op2** – you can see a letter from Fairchild's marketing department in 1968 which concludes, 'We've got a winner'. The various versions of the 741 have sold in hundreds of millions.

The 741 deserves its place as an iconic electronic component, but its popularity and ubiquitousness in textbooks and online tutorials can lead to problems when inexperienced designers assume that it will be suitable in circuits where it isn't. A common example of this is use at relatively low supply voltage circuits – the 741 datasheet (Texas Instruments, Rev D, 2015) specifies a recommended minimum supply voltage of ±10V. Maddan417's circuit runs on 5V, so the 741 is well outside its recommended operating conditions in this application.

Of course, the 741 will be OK in plenty of circuits where high performance and relatively low supply voltages are not required, and it is still likely to be found in commercial designs, many of which may have been around for a long time. On the other hand, the performance of the 741 is poor compared to more modern devices,

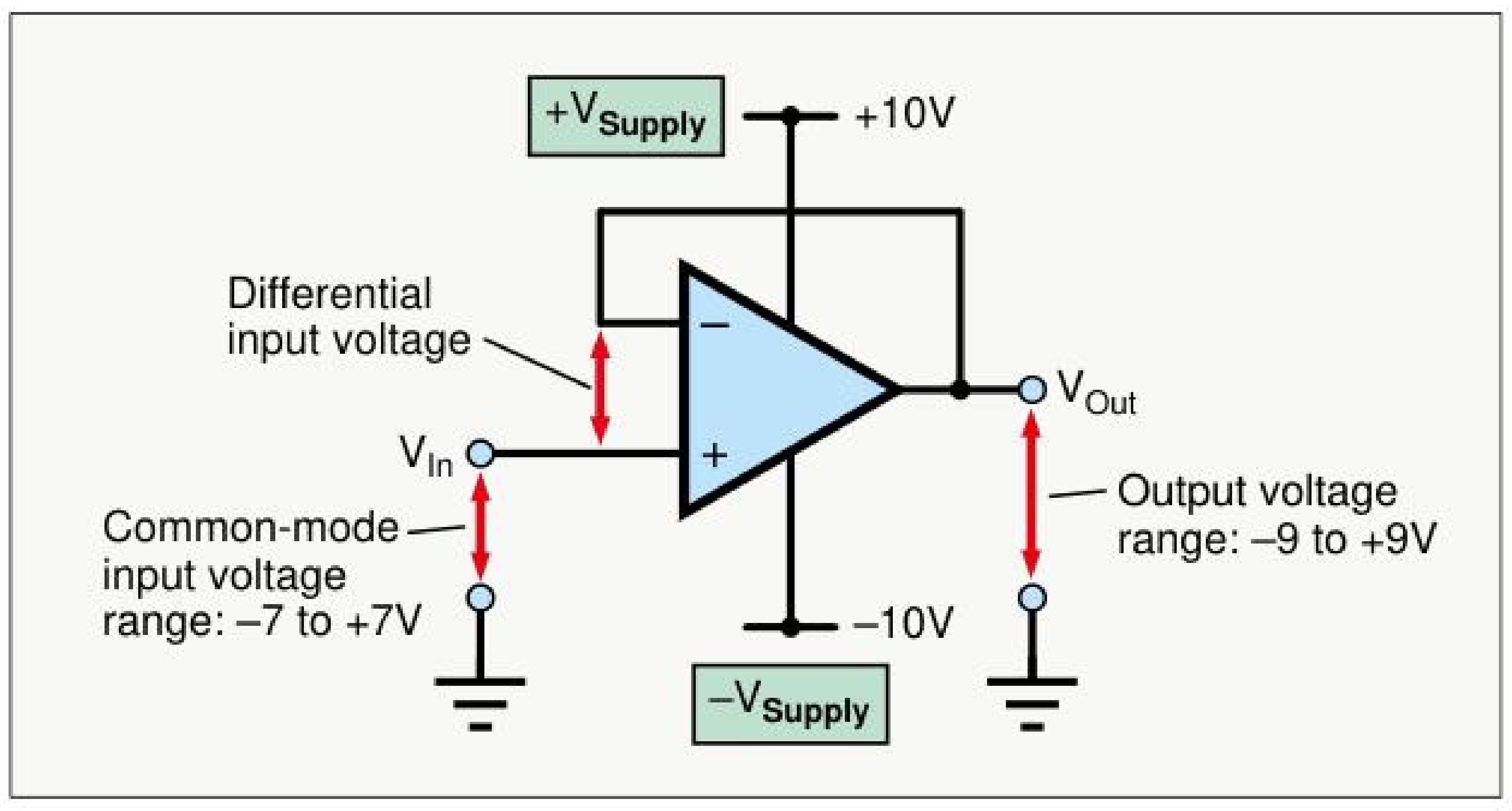

+V_Supply
+10V
Differential input voltage
V_In
Common-mode input voltage range: –7 to +7V
V_Out
Output voltage range: –9 to +9V
–10V
–V_Supply

Fig.2. Example op amp voltage ranges for split supply. For this circuit, for normal linear operation, the common-mode input voltage is equal to V_{in}.

so there is relatively little to justify using it in a new design, and many designers today would never consider it. However, its relatively high maximum supply voltage (44V/±22V), combined with low cost and well-understood behaviour are sometimes cited as a reasons for using it. There are, however, plenty of other op amps which operate at this, and higher voltages, so this is not in itself a unique property.

Voltage ranges

There are a few voltage ranges to consider when designing op amp circuits, and these op amp specifications must be compatible with the operating requirements of the circuit. We have already mentioned that the supply voltage range is a problem in Maddan417's circuit. The other voltage range parameters are the output voltage and input voltage ranges.

Op amps are often operated on split supplies – usually equal positive and negative supplies (see Fig.2). This enables the op amp circuit to easily handle AC signals (that have both positive and negative voltage excursions). A signal varying around 0V is conveniently in the middle of the supply range, which tends be where it is easiest to design op amp circuits to work effectively. As signals get closer to (or even beyond) the supply voltage range, op amp circuit design becomes more challenging. For example, transistors may turn off, or potentially damaging polarity reversals may occur, preventing correct operation. Many op amps, particularly earlier devices such as the 741, are not designed to handle signals close to the supply.

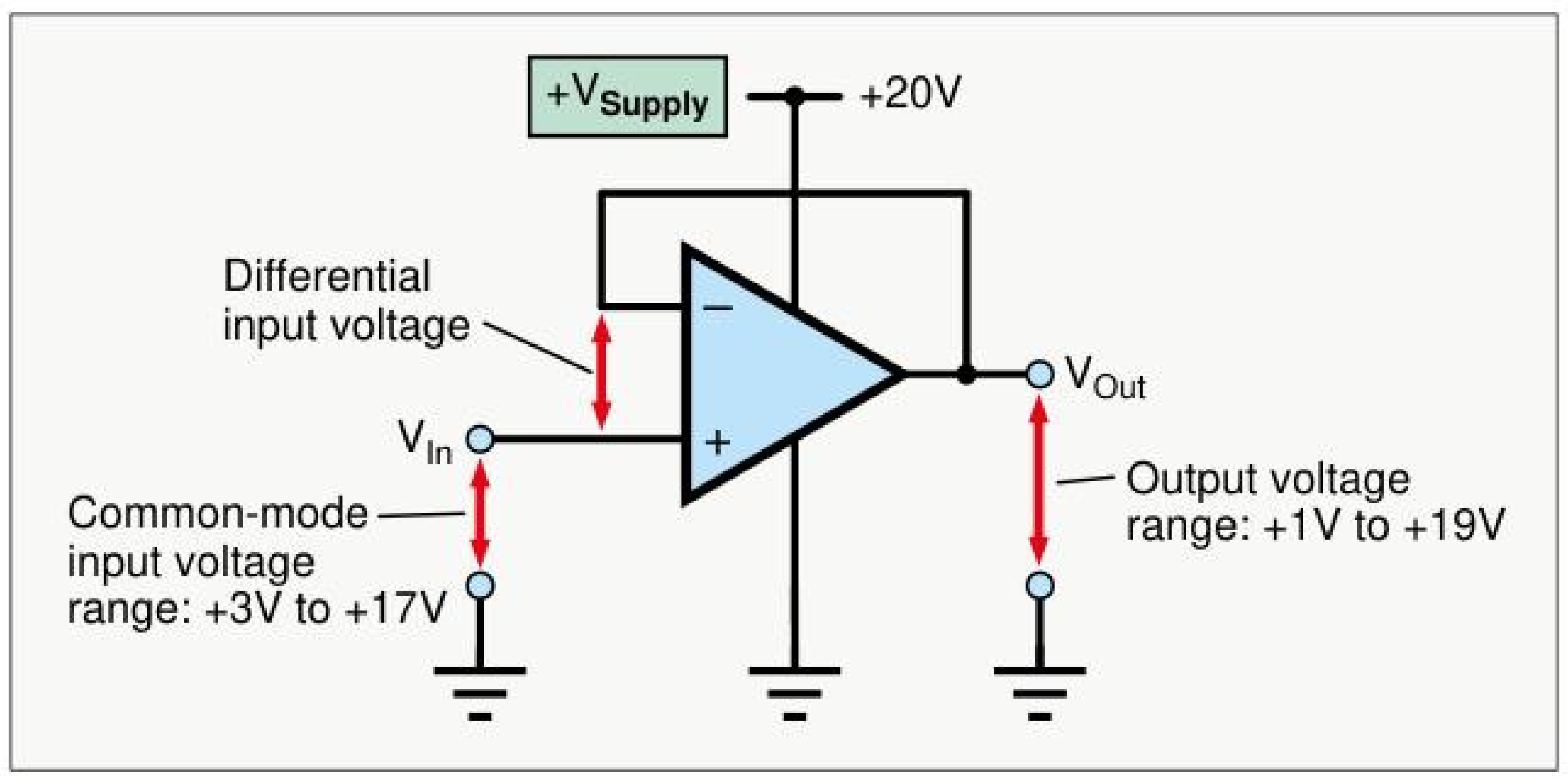

+V_Supply
+20V
Differential input voltage
V_In
Common-mode input voltage range: +3V to +17V
V_Out
Output voltage range: +1V to +19V

Fig.3. Example op amp voltage ranges for single supply. For this circuit, for normal linear operation, the common-mode input voltage is equal to V_{in}.

The maximum output voltage range (or output voltage swing) of an op amp is often specified relative to the supplies (under specific conditions). For example, 'within 1V of the supplies' would mean, on a ±10V supply, the output range would be ±9V (see Fig.2), on a single 20V supply it would be +1 to +19V (see Fig.3). The LM741's specified output range is ±12V to ±14V on ±15V supply (ie, within 1 or 2V of the supply) but is worse for loads below 10kΩ.

An op amp does not experience any fundamental difference operating on a split supply or a single supply of equal magnitude (eg, ±10V split or single 20V). An AC signal can have an offset applied to it so that it varies around the mid-point of a single supply. Thus, to the op amp, the conditions are the same for a ±5V output on a ±10V split supply, or a 5V to 15V output centred on 10V with a single 20V supply. However, there is often a requirement to handle signals specifically at, or close to 0V, which means that a single-supply circuit requires the op amp to output signals at or close to the supply, whereas a split supply does not. This is a problem for Maddan417's single-supply circuit where there is a requirement to output 0V when the comparator output is low – the 741 is not able to achieve this.

Over the last two or three decades supply voltages have tended to reduce due to the effects of advances in semiconductor technology. For example, op amps are often required in circuits together with digital devices, such as microcontrollers, which require low supply voltages. It is convenient to operate op amps on the same voltage, where possible, so there is demand for lower voltage op amps. If an op amp can only handle signals to within 1V of the supply this is much more likely to be a problem with a 3.3V supply than a 20V one. This, and the convenience of single-supply operation with outputs able to go 0V, have led to the development of op amps with 'rail-to-rail' outputs.

Typically, for BJT op amps, rail-to-rail outputs can go to within a collector-emitter saturation voltage (V_{CEsat}) of the supply. V_{CEsat} is dependent on the transistor's collector current and hence the op amp's output current. For moderate currents (in the mA range) V_{CEsat} is typically 100 to 300mV. Some op amp designs take things further and have internal circuits to generate voltages above and below the applied supply voltage to facilitate full rail-to-rail signal ranges.

Input voltages

Op amps have two inputs, so there are input voltage specifications relating to individual, differential and common-mode signals. Individual inputs have an absolute maximum voltage specification. For the 741 this is either the supply voltage or ±15V, whichever is lower. The differential voltage is the voltage between the inputs, again there is an absolute maximum rating for this, which is ±30V for the 741.

In most op amp applications, the op amp is used as an amplifier with feedback. This keeps the inputs at more or less the same voltage, so differential input limitations are not an issue for normal operation. However, if used as a comparator, or if a linear amplifier is pushed into saturation by a large input signal, then larger differential inputs can occur.

The common-mode input voltage is the average of the voltage on the two inputs. For non-inverting amplifiers and similar configurations (see Fig.3) the common-mode input is equal to the input voltage (remember the two inputs are at about the same voltage). Common-mode input range may also be specified relative to the supplies – for example, within 3V of the supplies, as shown in Fig.3. As with output ranges, some op amps have rail-to-rail common-mode input capability. The common-mode input range figure is not always quoted for the 741, but the Harris CA741 datasheet (1993) states ±12V for ±15V supplies, indicating within 3V of the supplies.

Op amps as comparators

Op amps can be used as comparators, but there are dedicated comparator chips which perform this function much better. In general, a dedicated comparator should always be used, but in some cases, for example where the comparator requirements are not demanding and/or a spare op amp is available on a multi-op-amp package then they can be used. The following discussion will highlight the differences between op amps and comparators.

A comparator's output will typically switch between the positive and negative supply voltages (or ground and supply in single-supply circuits), going rail-to-rail, or sufficiently close to be easily interpreted as a logic 0 or 1, or to switch a transistor or other load effectively. For similar behaviour from an op amp, a rail-to-rail output device must be used, otherwise the problems observed with Maddan417's circuit will occur. Comparators have no need to output intermediate voltages; however, the output may switch (or it may be possible to arrange for it to switch) to a *different* voltage from the main comparator supply to facilitate interfacing to logic circuits, or for switching loads on different

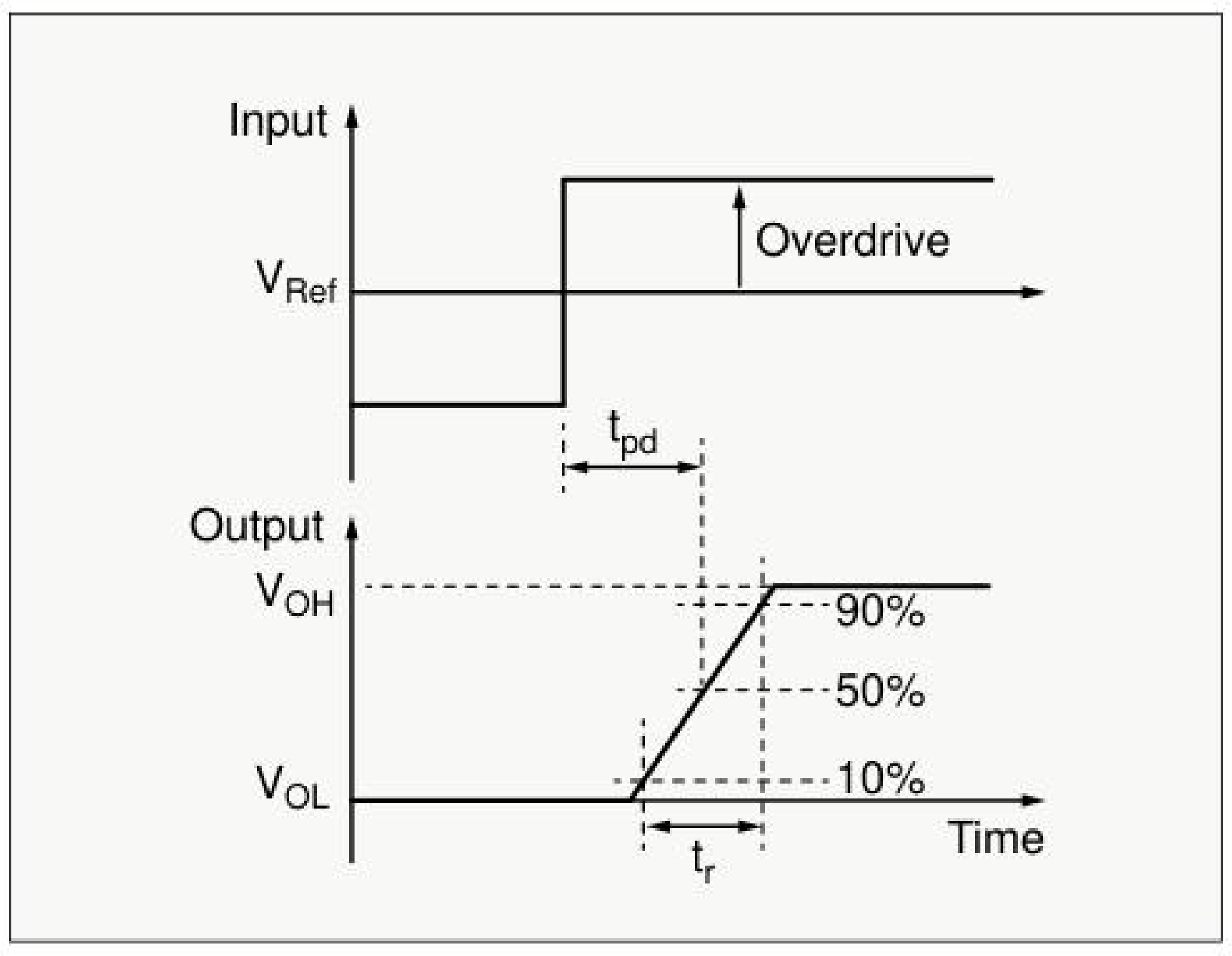
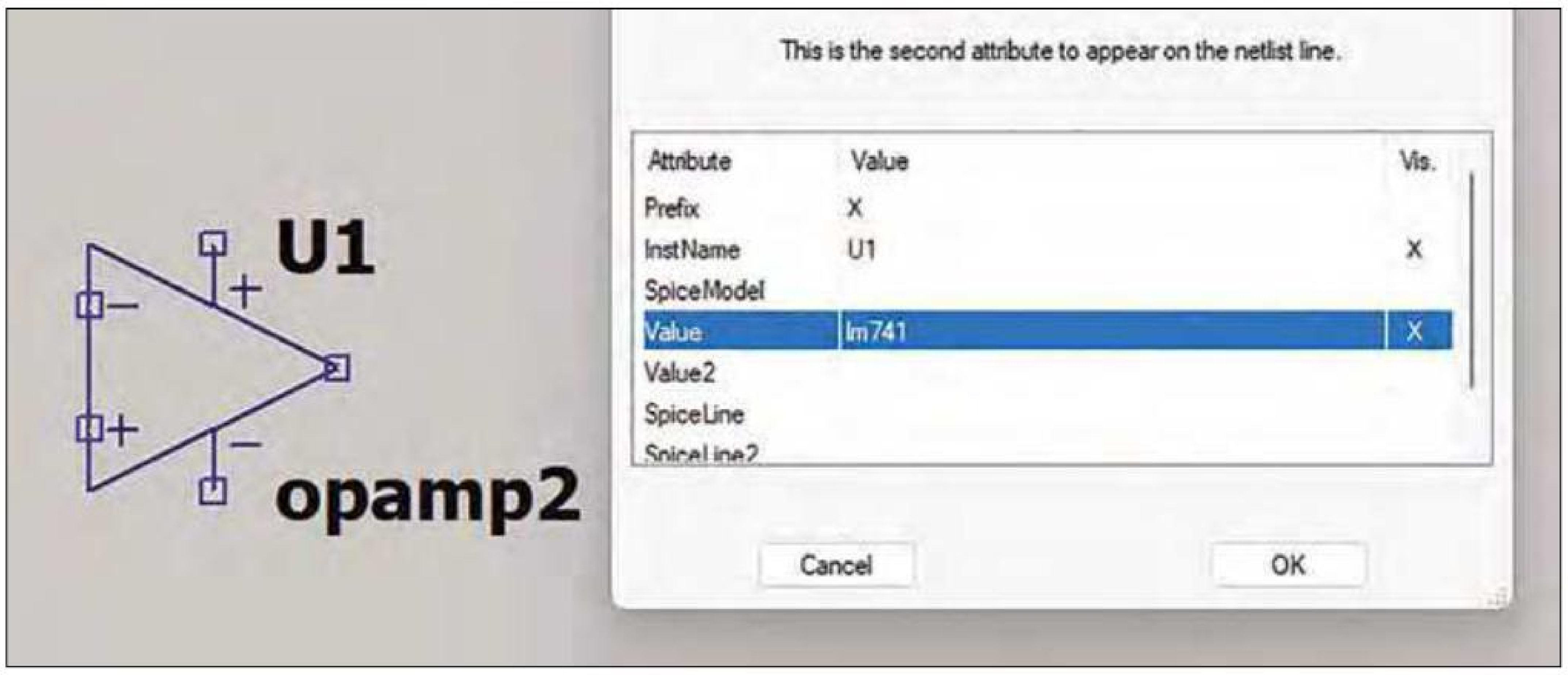


Fig.4. Comparator propagation delay.



This is the second attribute to appear on the netlist line.

Attribute	Value	Vis.
Prefix	X	
InstName	U1	X
SpiceModel		
Value	lm741	X
Value2		
SpiceLine		
SpiceLine2		

Fig.5. Configuring opamp2 to use the lm741 subcircuit.

supplies. This is more difficult to achieve with op amps.

Often, comparator output circuits are designed to be easy to interface with specific types of logic. Comparators are therefore available with a variety of output configurations including push-pull, open drain, open collector and LVDS (low-voltage differential signalling). Open drain and open collector require an external (pull-up) resistor connected from the output to the positive (digital) supply.

Op amps are designed to be used with negative feedback – a 'closed-loop' system. All amplifiers have some delay from input to output, which results in increasing phase shift as signal frequency increases. At some point the phase shift reaches 180°, at which point the negative feedback network is actually delivering positive feedback. If the gain of the amplifier and feedback network together is greater than one at this frequency then oscillation will occur. The gain of most op amps is deliberately rolled off as frequency increases to prevent this instability – this is called compensation. Comparators are either used in 'open-loop' mode, or with positive feedback, so compensation is not required, leading to significant differences between the two types of devices.

Op amps are high-gain, linear, differential amplifiers; so, as already noted, in normal operation the voltage difference between an op amp's inputs is very small (typically microvolts to millivolts). Comparators often have much larger input differences. Not all op amps can tolerate large input voltage differences and they perform very poorly under such conditions. Op amp input impedance may drop significantly for large input differences due to conduction of protection diodes – this could upset circuits driving an op amp used as a comparator. Comparators are commonly used to compare voltages which are not close to half the supply range. For an op amp, this is a large common-mode input voltage. Again, not all op amps perform well under such conditions. If the common-mode input range is exceeded correct operation may not occur.

Gain and offset are characteristics shared by op amps and comparators, however, the switching behaviour of comparators means that they have characteristics related to switching which are not relevant to the standard analogue amplifier usage of op amps. The switching characteristics are illustrated in Fig.4.

Speed of switching

When the comparator input voltage crosses the reference voltage the comparator output will switch. This will not happen instantaneously – the time taken for the comparator output to reach 50% of the resulting voltage change is the propagation delay (t_{pd}). The time taken for the comparator output voltage to rise from 10% to 90% of its range is the rise time (t_r). The amount of voltage applied to the comparator's input beyond the switching threshold (reference voltage) is known as the overdrive. Propagation delay and rise time are usually sensitive to overdrive, with increasing overdrive resulting in faster switching times. Comparator speed is also usually dependent on supply voltage.

The maximum rate of change of output voltage an op amp or comparator can deliver is the slew rate. Slew rate is important for op amps because it indicates how well the output voltage will track fast-changing analogue waveforms; failure to do so causes distortion. Slew rate also directly determines the maximum frequency at which an op amp can produce a pure sinewave at full output swing (the full power bandwidth), however, sinewave output is of no relevance to comparators.

For any circuit used as a comparator, either the slew rate or the bandwidth may be the dominant factor in determining the propagation delay. Because comparators are just required to switch their outputs quickly the slew rate itself is not usually very important as a specification, it is the propagation delay and rise time which are quoted. The compensation applied to op amps tends to reduce their slew rate, making them relatively slow when used as comparators.

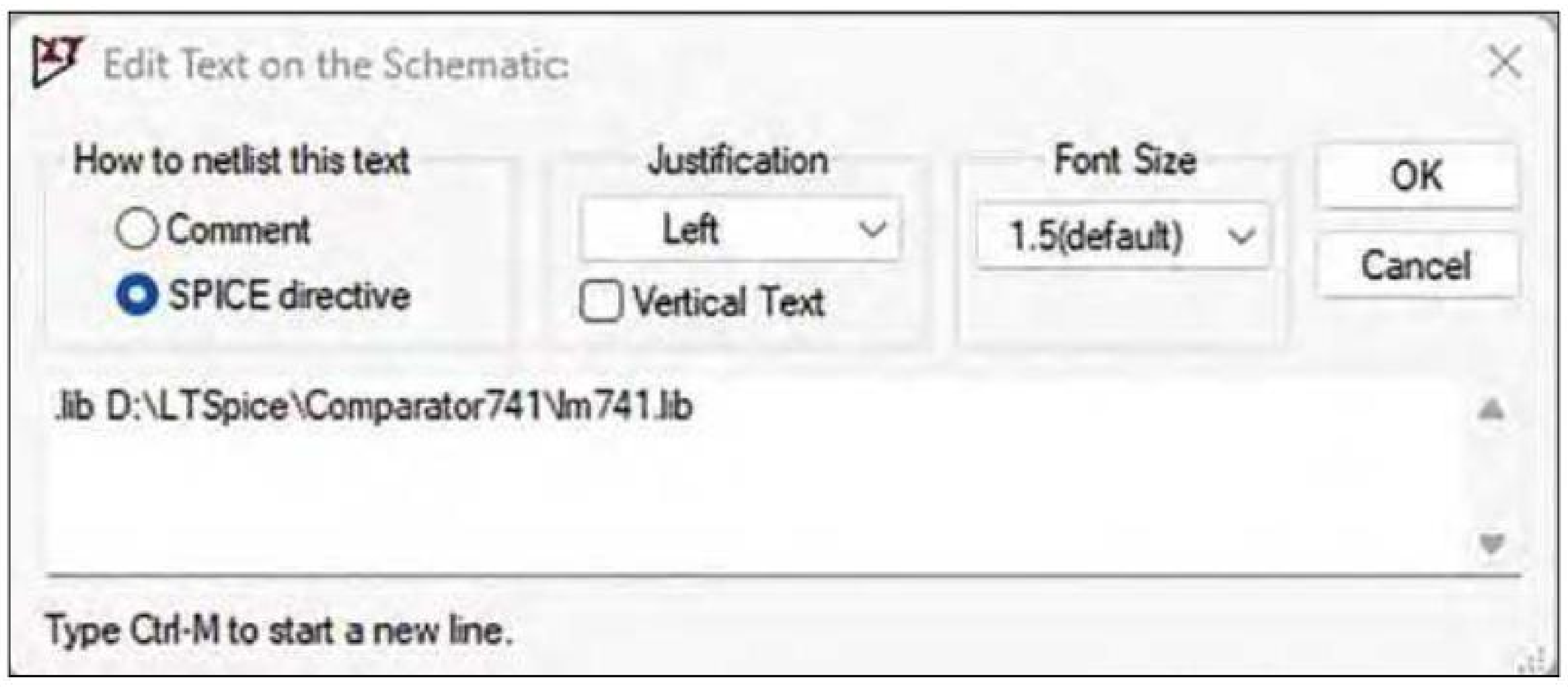
Op amps are designed for applications where the output voltage does not go hard to the supply rails – this would normally imply clipping of the waveform and hence distortion. When op amp outputs are driven hard into saturation they tend to be slow to recover. Like compensation, this makes op amps poor comparators where fast switching is required. The internal circuitry of comparators is different, allowing them to recover very quickly. A further subtlety to this is that op amp saturation recovery time is likely to vary between individual devices, making the propagation delay somewhat unpredictable.

Simulating the 741

We can simulate a 741 comparator circuit and compare it with a dedicated comparator using LTspice. However, this takes some effort as there is no 741 model provided as part of the LTspice download. If you search online for '741 SPICE model' you will find a link on the Texas Instruments site for a 'LM741 PSPICE Model' (note Pspice, *not* LTspice): **https://bit.ly/pe-may23-741**

The download provides an **lm741.lib** file, which is a SPICE subcircuit definition. This code can be used, together with an appropriate associated symbol file to allow the model to be included in an LTspice schematic. Do be aware that although

Fig.6. Entering the .lib directive.



How to netlist this text
○ Comment
● SPICE directive

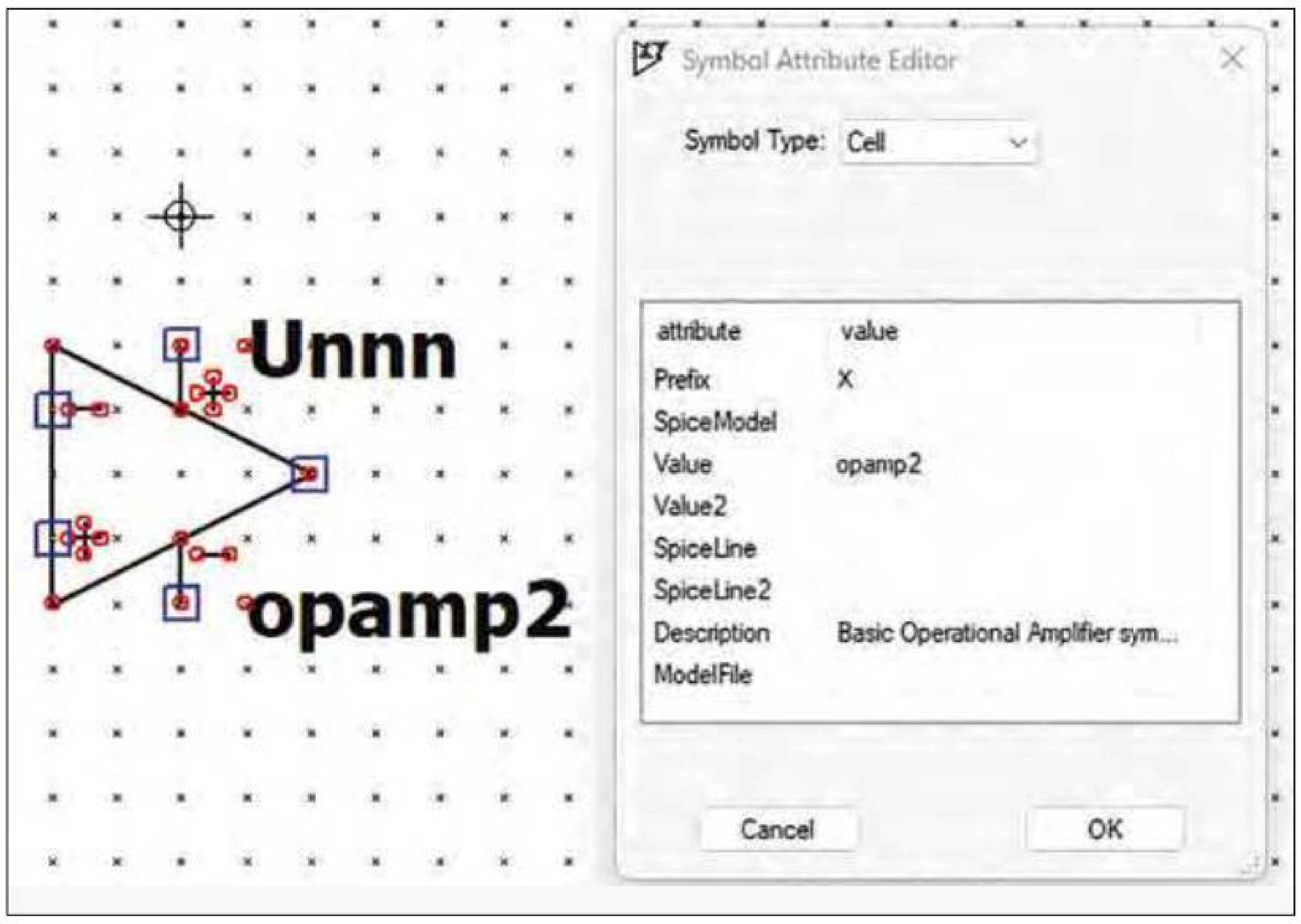
Justification: Left

☐ Vertical Text

Font Size: 1.5(default)

```
.lib D:\LTSpice\Comparator741\lm741.lib
```

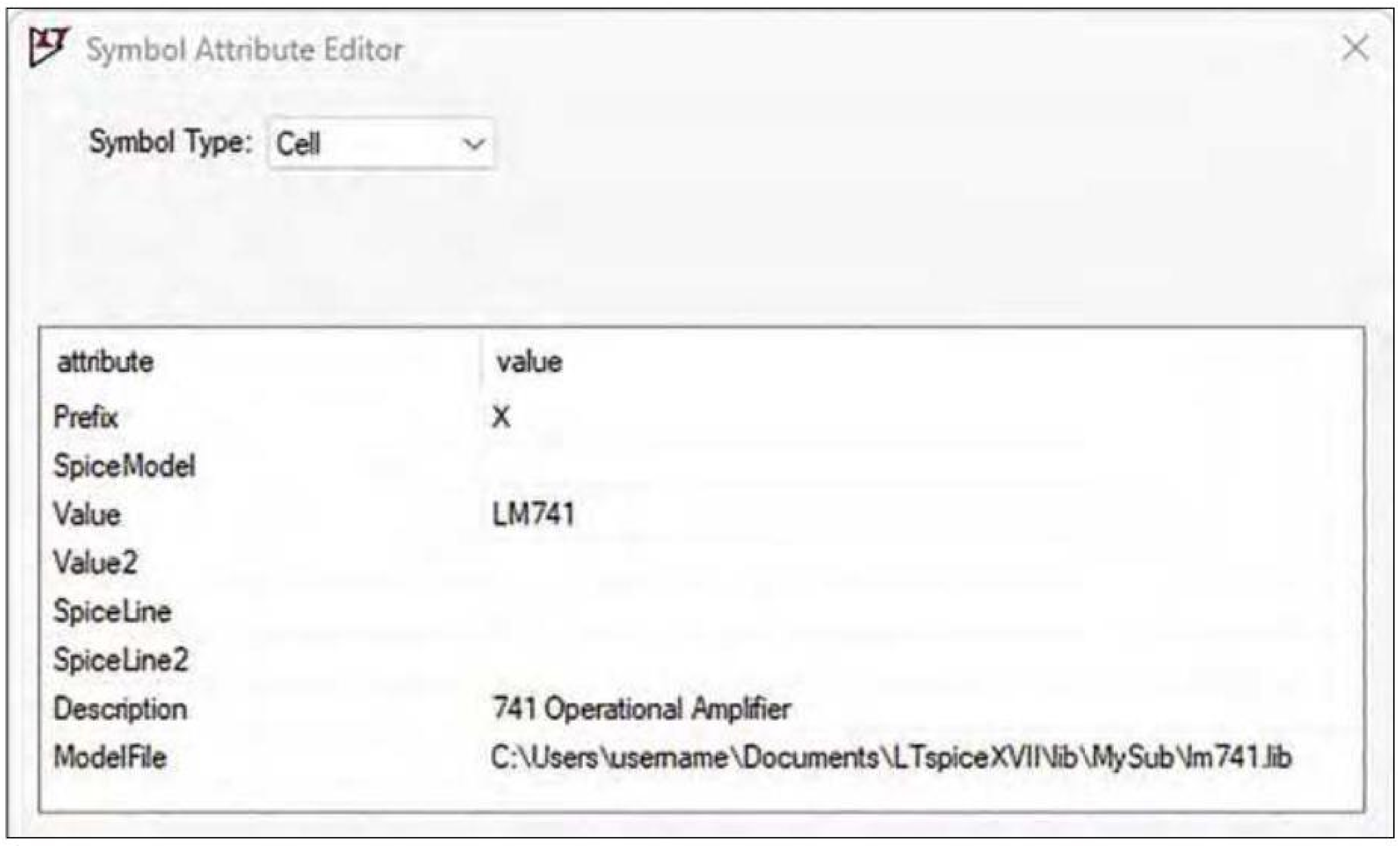
Type Ctrl-M to start a new line.



Symbol Type: Cell

attribute	value
Prefix	X
SpiceModel	
Value	opamp2
Value2	
SpiceLine	
SpiceLine2	
Description	Basic Operational Amplifier sym...
ModelFile	

Fig.7. Symbol Attribute Editor for a component in the library.



Symbol Type: Cell

attribute	value
Prefix	X
SpiceModel	
Value	LM741
Value2	
SpiceLine	
SpiceLine2	
Description	741 Operational Amplifier
ModelFile	C:\Users\username\Documents\LTspiceXVII\lib\MySub\lm741.lib

Fig.8. Configuring the LM741 symbol attributes.

SPICE is a de facto standard, and hence models are often compatible, sometimes it is necessary to edit models created for a different SPICE tool. Fortunately, in this case, the model works with LTspice. The 741 model can be used as a one-off, or added to the LTspice library so that it can be used like other components.

For one-off use, place the downloaded **lm741.lib** file in the folder to be used for the circuit simulation files. Create a new schematic in the same folder, using the opamp2 component (from the Opamps part of the component selector) where you need a 741. Right click on the symbol and change the Value attribute to `lm741` (see Fig.5). Then click on the SPICE Directive (`.op`) button and enter the `.lib` command with the full path to the **lm741.lib** file (see Fig.6), for example:

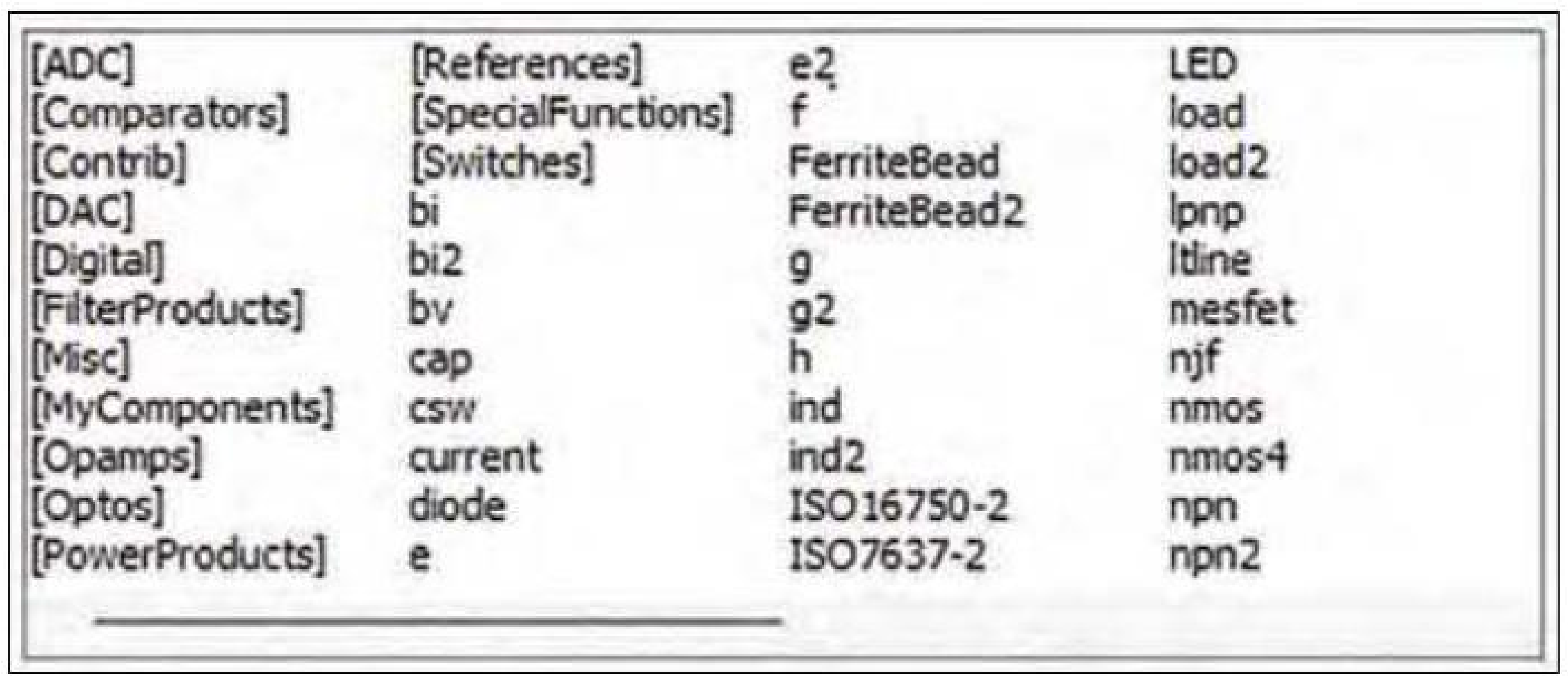
```
.lib D:\LTSpice\Comparator741\lm741.lib
```

(Do remember to use the path to the file on *your* computer.) Click to place the directive text on the schematic.

Adding components to the LTspice library

It is possible to create a new folder in the LTSpice library that will appear on the list of components when editing schematics. Placing symbol files in this folder and associating these with `.lib` SPICE model files downloaded from manufacturers will make those components available for use in any simulation. The following instructions describe what to do for the 741, but other models can be added using this procedure.

Find the location of the LTspice symbols library (**sym** folder) on your computer (eg, **C:\Users\username\Documents\LTspiceXVII\lib\sym**) and create a new subfolder here with a name of your choice (eg, **MyComponents**). Copy (not move!) the **opamp2.asy** symbol file from the **Opamps** subfolder of the existing **sym** folder to your new subfolder and rename the new file **lm741.asy**.



[ADC]
[Comparators]
[Contrib]
[DAC]
[Digital]
[FilterProducts]
[Misc]
[MyComponents]
[Opamps]
[Optos]
[PowerProducts]
[References]
[SpecialFunctions]
[Switches]
bi
bi2
bv
cap
csw
current
diode
e
e2
f
FerriteBead
FerriteBead2
g
g2
h
ind
ind2
ISO16750-2
ISO7637-2
LED
load
load2
lpnp
ltline
mesfet
njf
nmos
nmos4
npn
npn2

Fig.9. New folder in the component selector.

Also create another new folder for the model file – a subfolder of **...\Documents\LTspiceXVII** is appropriate, with a name like **MySub** (the folder with the original LTspice model files is called **Sub**). Put the downloaded **lm741.lib** file in your new folder.

Go to you your symbol folder and double-click the **lm741.asy** file to open it in the LTspice symbol editor. Alternatively, open LTspice and do File > Open. In the file open dialog change the file type to Symbols (*.asy) and open the **lm741.asy** file.

Then, in LTspice open the symbol attribute editor from the menu using:

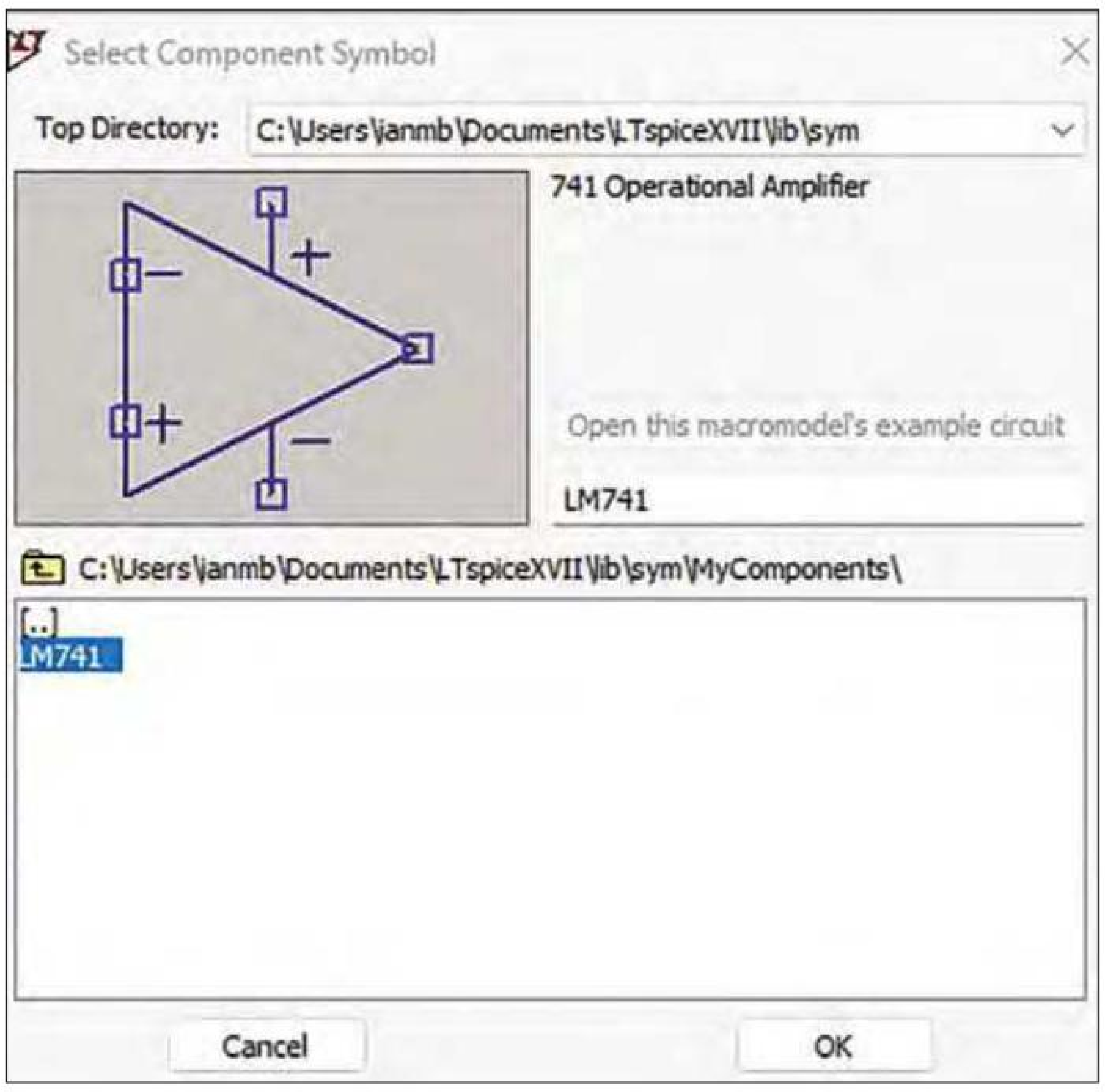
Edit > Attributes > Edit Attributes

Referring to Fig.7, in the Symbol Attribute Editor change the Value attribute to LM741 and insert the full path to the **lm741.lib** file as the Modelfile attribute value. You can also add a description if you want (see Fig.8). Save the symbol and close LTspice.

Open LTspice and create a new schematic. When you add a component, the new folder in the symbol library should be listed (See Fig.9). In this folder you will find the LM741 (see Fig.10), which can be added to the schematic in the usual way. Note that the Description attribute is displayed in the component selector along with the symbol.

LT1018 vs LM741 simulation

Fig.11 shows an LTspice schematic for comparing the 741 with a comparator. The comparator is an LT1018, which is



Top Directory: C:\Users\ianmb\Documents\LTspiceXVII\lib\sym

741 Operational Amplifier

LM741

C:\Users\ianmb\Documents\LTspiceXVII\lib\sym\MyComponents\

[..]
LM741

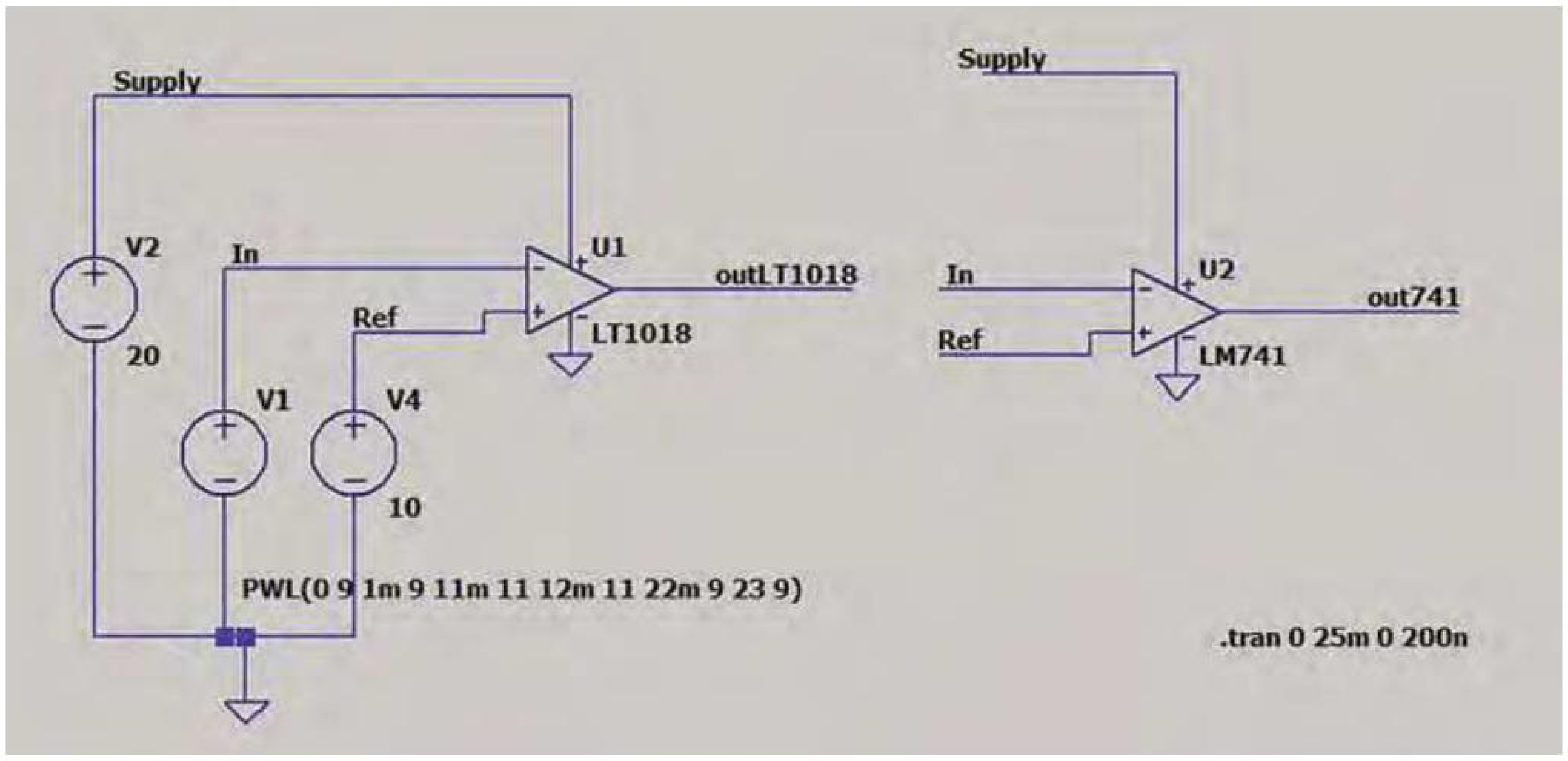
Fig.10. LM741 in the component selector.

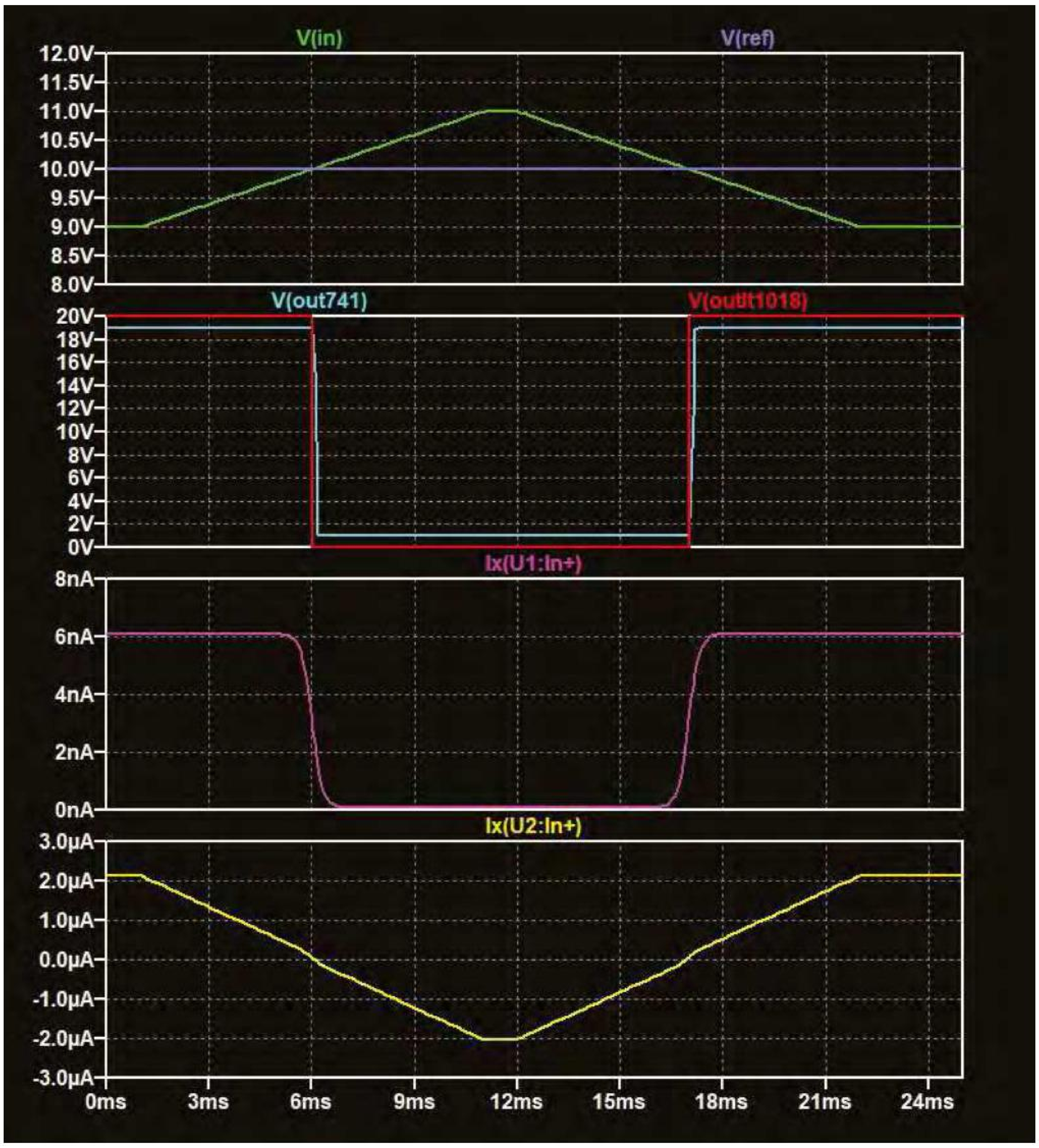
Top to bottom:

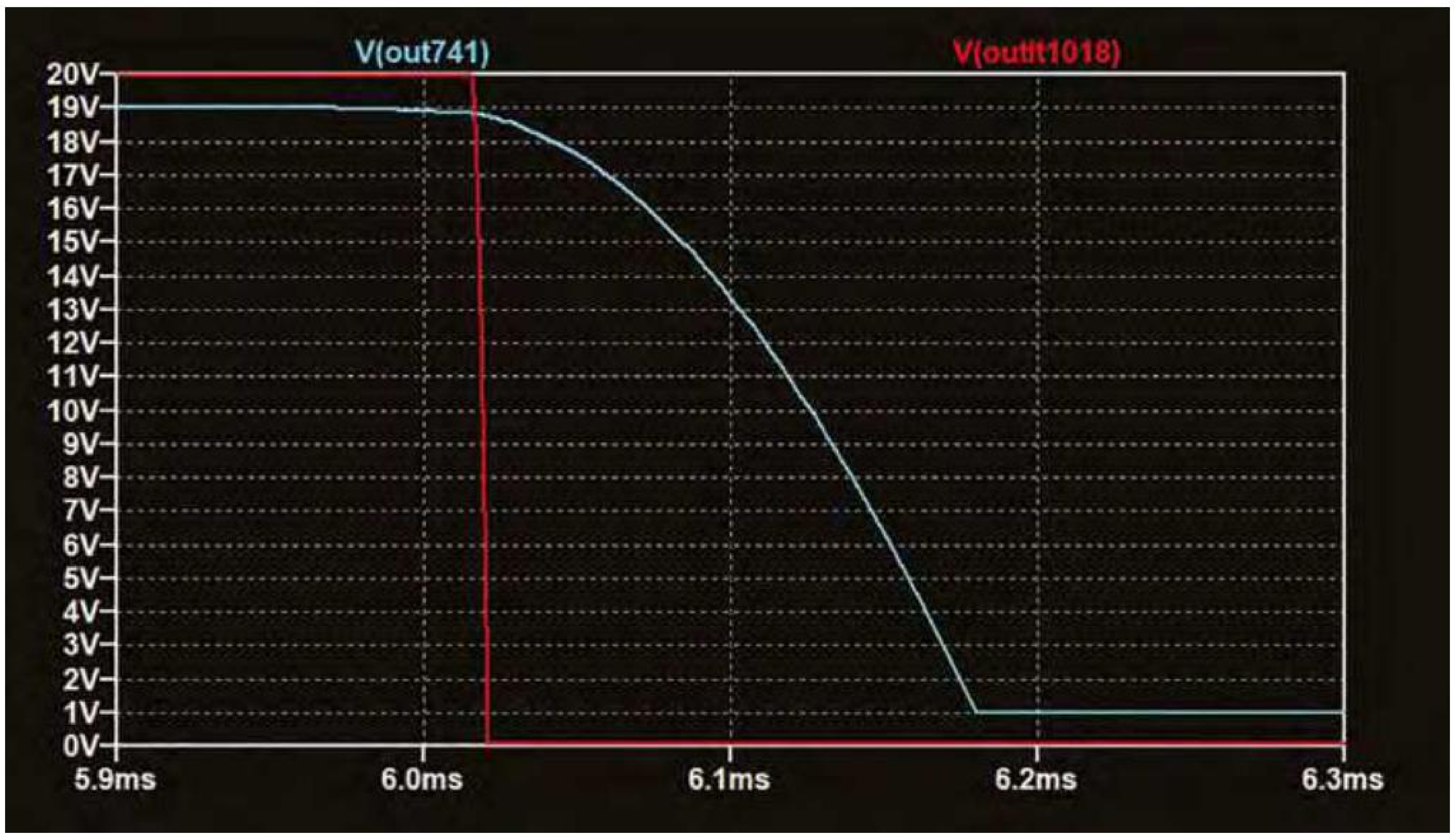
Fig.11. LTspice simulator schematic for comparison of an LT1018 comparator with an LM741 op amp when it is used as a comparator.

Fig.12. Results from simulation circuit shown in Fig.11.

Fig.13. Results from simulation circuit shown in Fig.11 (zoom in on output switching). Input threshold is crossed at 6ms.







available in the LTspice library. The output stage of the LT1018 includes a pull-up current source, eliminating the need for an external resistor, which is commonly needed with similar comparators like the LM393. The simulation uses both devices in a basic comparator configuration on a single supply, which is 20V to correspond with the LM741 recommended minimum. The comparator reference is at the centre of the supply range. This provides conditions which should not take the 741 out of its recommended operating conditions. This doesn't match Maddan417's circuit, but we can't be confident that the 741 model works well outside the recommended conditions.

The results of the simulation are shown in Fig.12, and Fig.13 shows a zoom in on the output switching. These shows that the output of the LM741 only gets to within about ±1V of the supplies – as described by Maddan417 and discussed above. The LT1018's output goes to values very close to the supplies. This again highlights the fact that interfacing an op amp output to logic or load switching is often more difficult than with a comparator device.

The simulation (Fig.13) also shows the LM741 op amp responds much more slowly than the LT1018 comparator, as discussed above. Finally, Fig.12 show the current into the non-inverting inputs of the two devices. The current into the LT1018 is orders of magnitude lower than for the 741. In general, old op amp designs have much higher input currents than modern devices. This may be very significant in some applications. Op amps can be used as comparators, but not without difficulties, and only in relatively slow-speed applications – the op amp's datasheet should be consulted to make sure that it is suitable for the application to avoid problems such as those experienced by Maddan417.

Simulation files

Most, but not every month, LTSpice is used to support descriptions and analysis in *Circuit Surgery*.
The examples and files are available for download from the *PE* website.

AUDIO OUT

By Jake Rothman

Op amp adaptor boards: surface mount and through-hole versions

Over the last few issues, we've described some general-purpose audio op amp boards designed for single and dual op amps. While I was designing these, it also seemed like a good idea to make some general-purpose adaptor boards to allow different package op amps to be adapted to any socket. For example, for the dual op amp board covered last month I wanted to compare a pair of single op amps with a dual device without changing anything else. To achieve this, I designed a special adaptor board to allow two 8-pin single op amps to be plugged into a socket with the pinout for one 8-pin dual op amp.

I liked the idea and decided to take this concept further, producing a board that enables two 8-pin dual op amps to be plugged into a 14-pin quad op amp socket.

Once I had sorted that out for DIL (dual-in-line) ICs I realised that it would be just as useful to have SMD (surface-mount device) versions of these adaptors. This would not only make the assemblies more compact, but also allow the use of some new op amps that are only available in SMD packaging. One important point to note here: there are quite a few varieties of SMD packaging, I have opted to use the most-common 8-pin SOIC.

The result is four adaptor boards. (Note that 8-pin-op-amp-SMD-to-DIL adaptor boards are also available from companies such as HobbyTronics Ltd – Fig.1, **https://bit.ly/pe-may23-dil** – and I will produce one of these too.

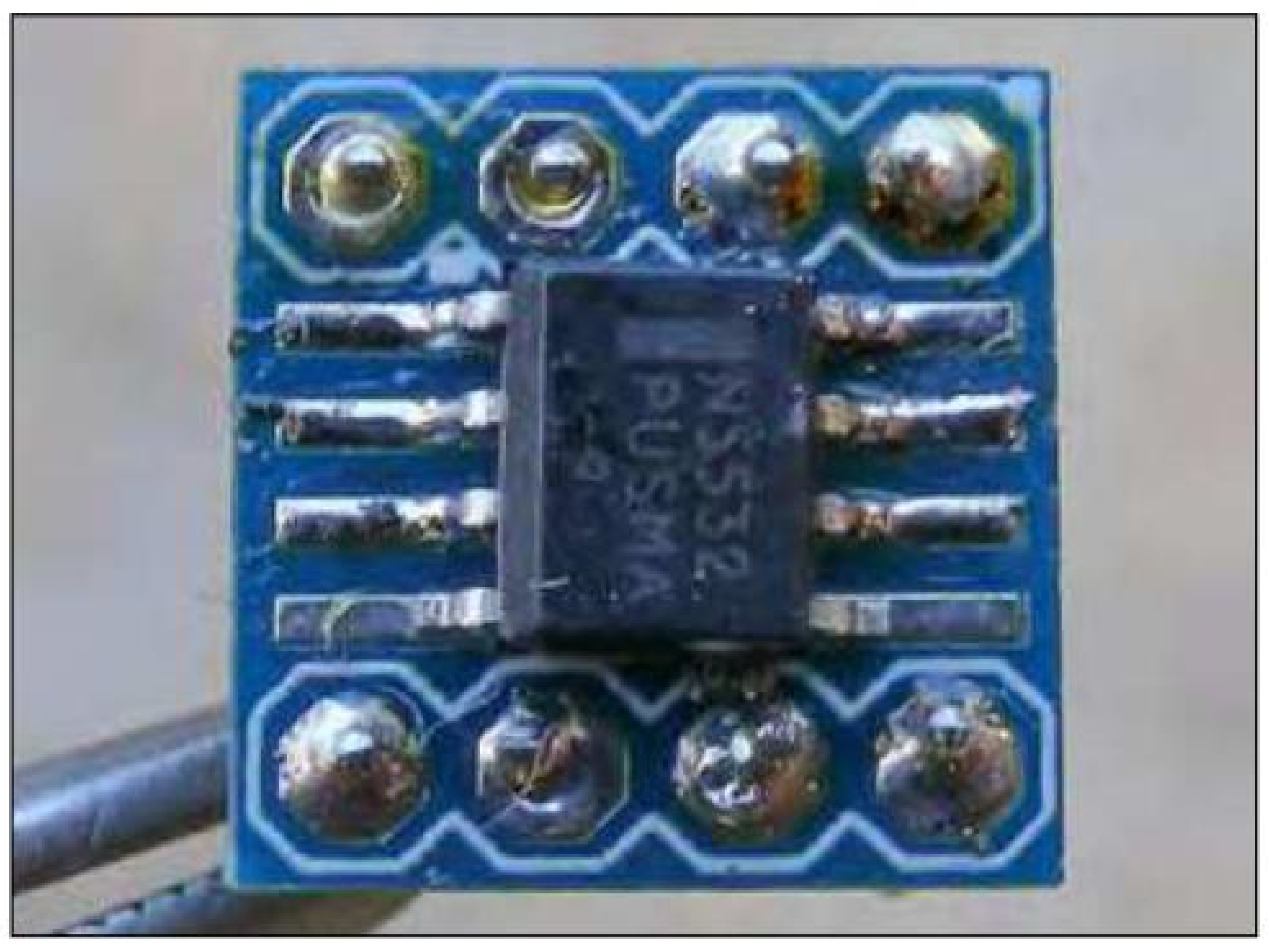


Fig.1. The original inspiration for these adaptor boards: an SMD-to-DIL op amp adaptor board from HobbyTronics.

Replacements and upgrading

Audio engineers don't like to waste money, and like grumpy farmers, they expect all equipment to last at least 50 years. Unfortunately, some op amp designs become obsolete and can be hard to find, but on the up side, new versions may well have much better noise and distortion figures. There's no point scouring eBay for replacement NOS (new-old-stock) quad-pack 741-style devices – it's much better to replace expired op amps with some NE5532s.

J-FET replacements

A quick word or two of advice here. If you're working on old equipment that uses J-FET input op amps, such as the 1980s Texas Instruments TL0xx Bi-Fet series, then it's essential to use J-FET replacements because bipolar input op amps have much higher input bias currents. If a bipolar NE5532 is used to replace a TL072 in a mixer channel or preamplifier then then the result is likely to suffer from switch clicks and pot scratching. While the bias currents could be blocked by adding extra coupling capacitors and DC path resistors, it is a lot of work, probably involving track cutting. Good audio J-FET op amps tend to be very expensive, such as the Burr Brown designs. There is only one relatively low-cost replacement for the TL072, the SMT-only Nisshinbo NJM8087, distributed by Profusion. Mouser also stock them, but they are pricey.

Texas Instruments have taken over a lot of the National Semiconductor, Analogue Devices and Burr Brown op amps. The TI OPA134 SoundPlus FET series are one of the best, but they're expensive.

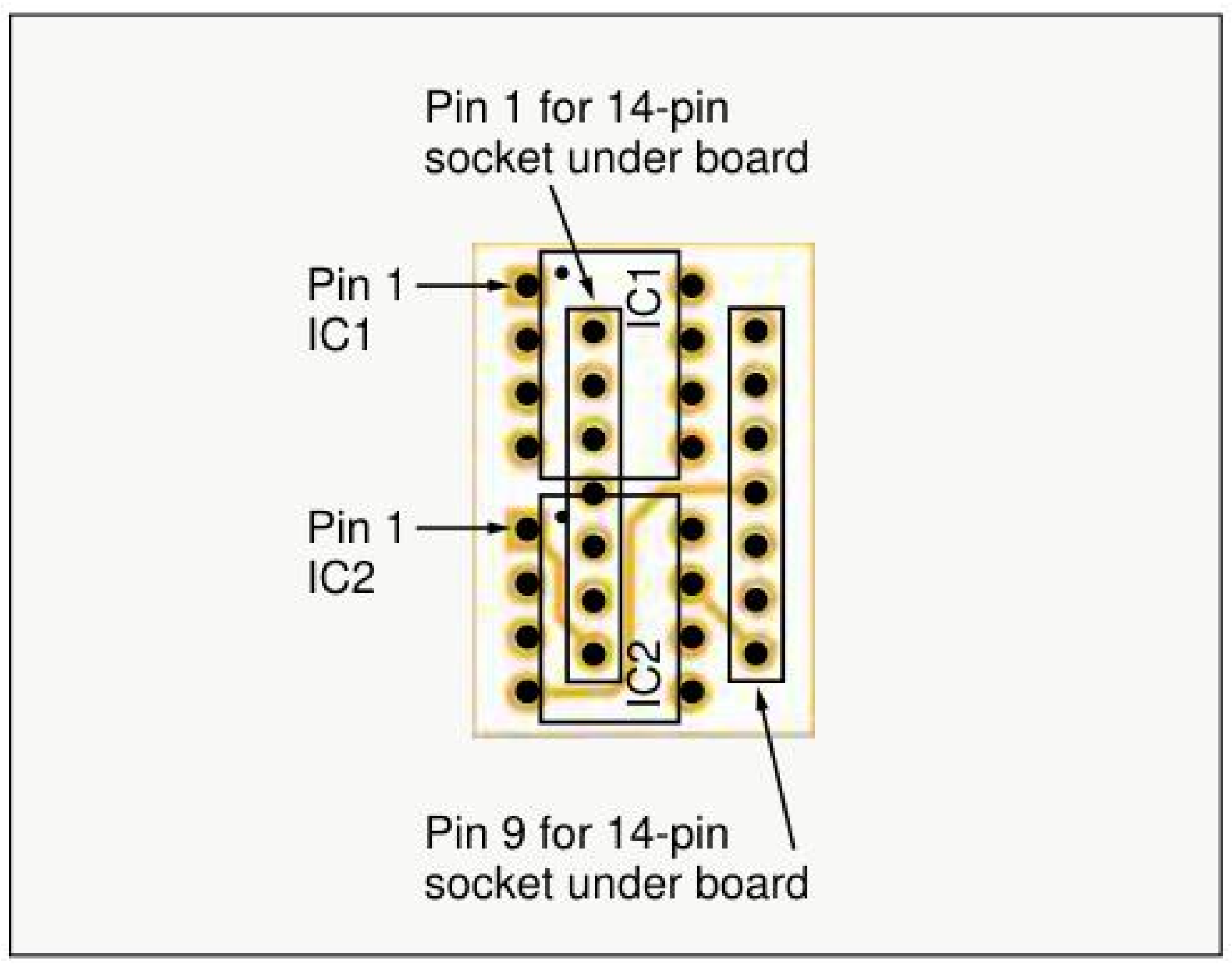

Pin 1 for 14-pin socket under board
Pin 1 IC1
IC1
Pin 1 IC2
IC2
Pin 9 for 14-pin socket under board

Fig.2. Overlay for the two-duals-to-quad op amp adaptor board.

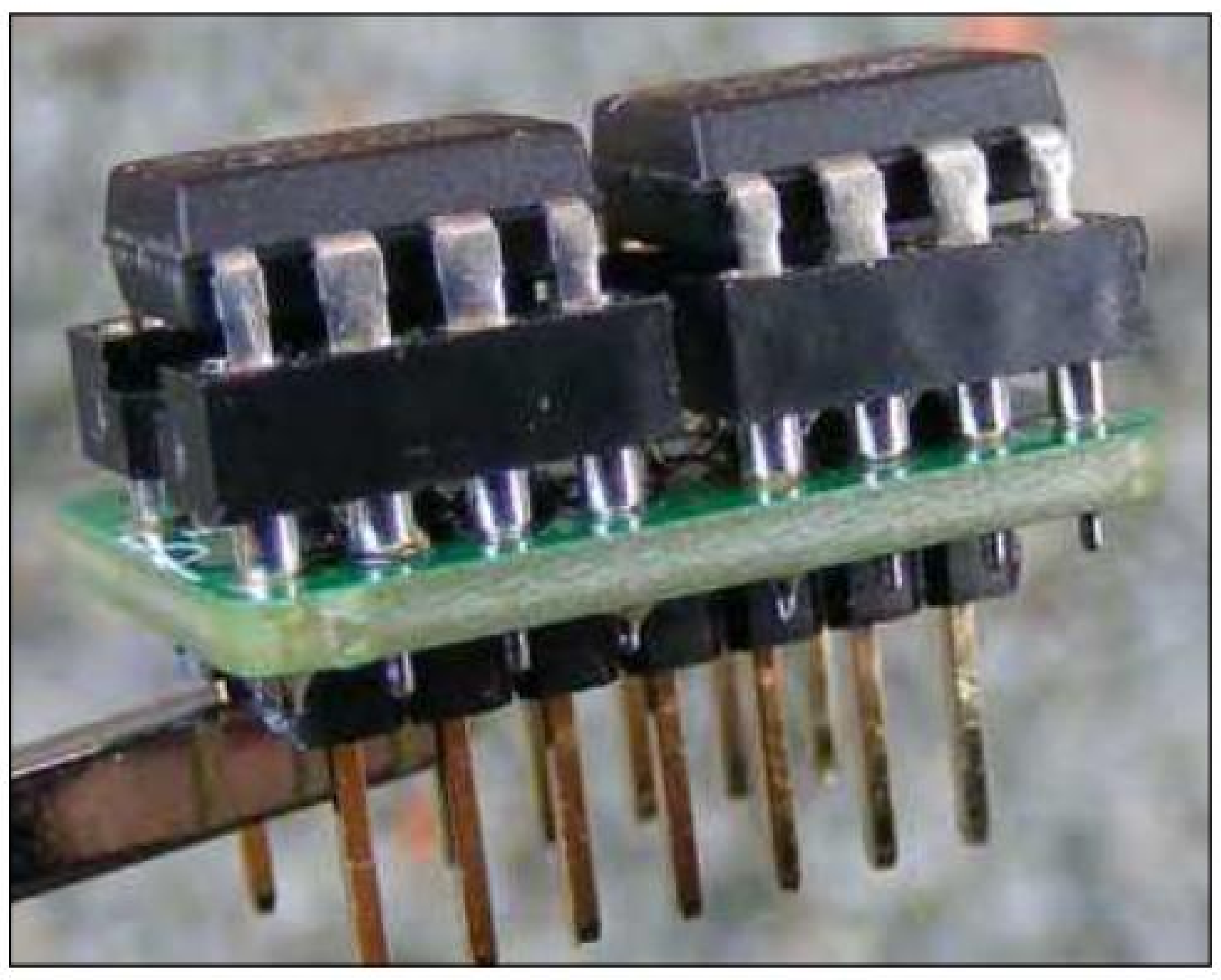


Fig.3. The two-duals-to-quad adaptor board assembled.

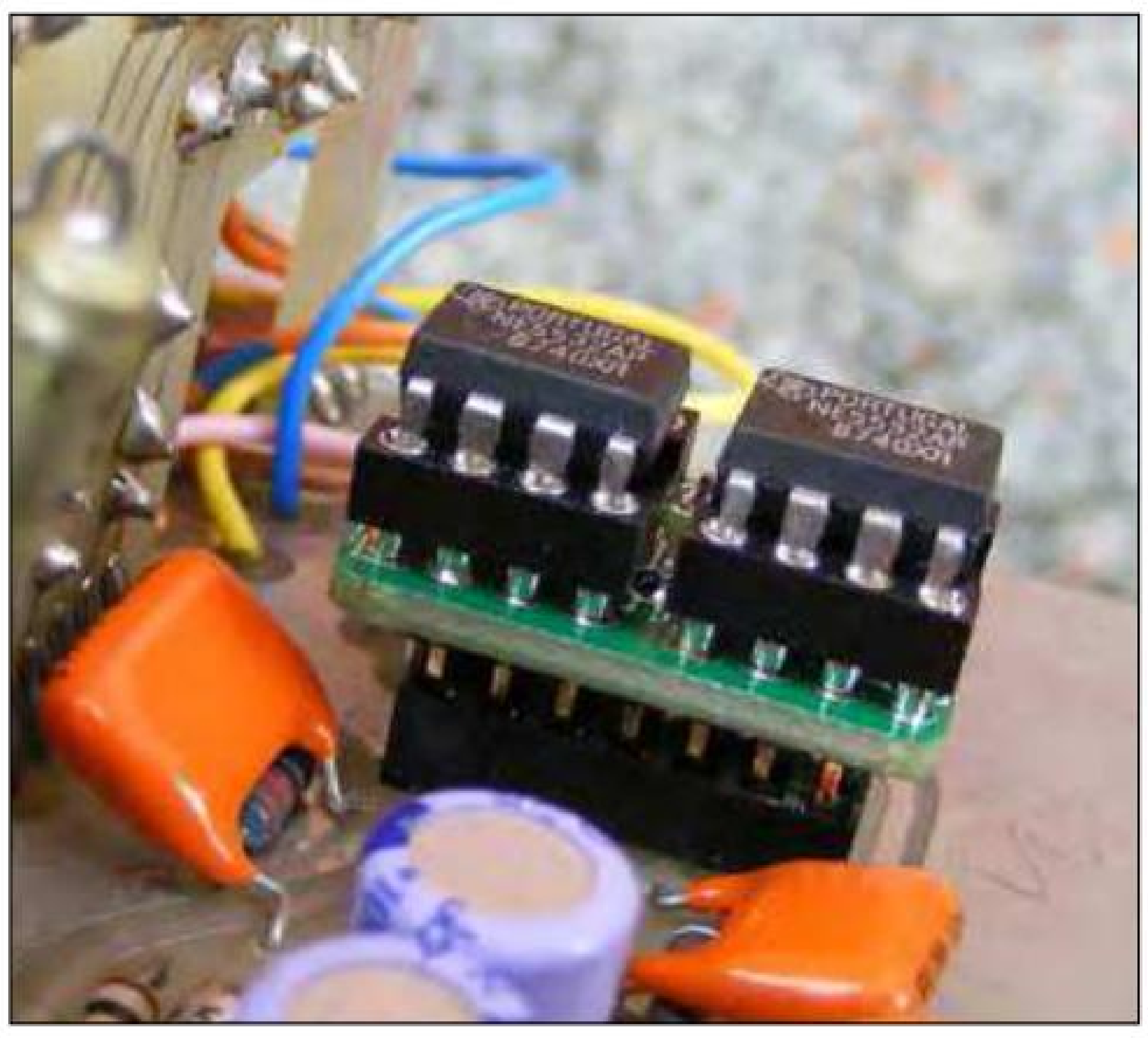


Fig.4. The two-duals-to-quad adaptor installed in an old Audio Developments mixer channel strip.

Discontinued early Fairchild J-FET op amps (eg, the µA771 and 772) occasionally pop up in late-1970s equipment such as mixing desks from Electrosonic and Soundcraft. Likewise, the LF351, LF353, LF356, LF441 and TL082 are similar second generation Bi-Fets. All

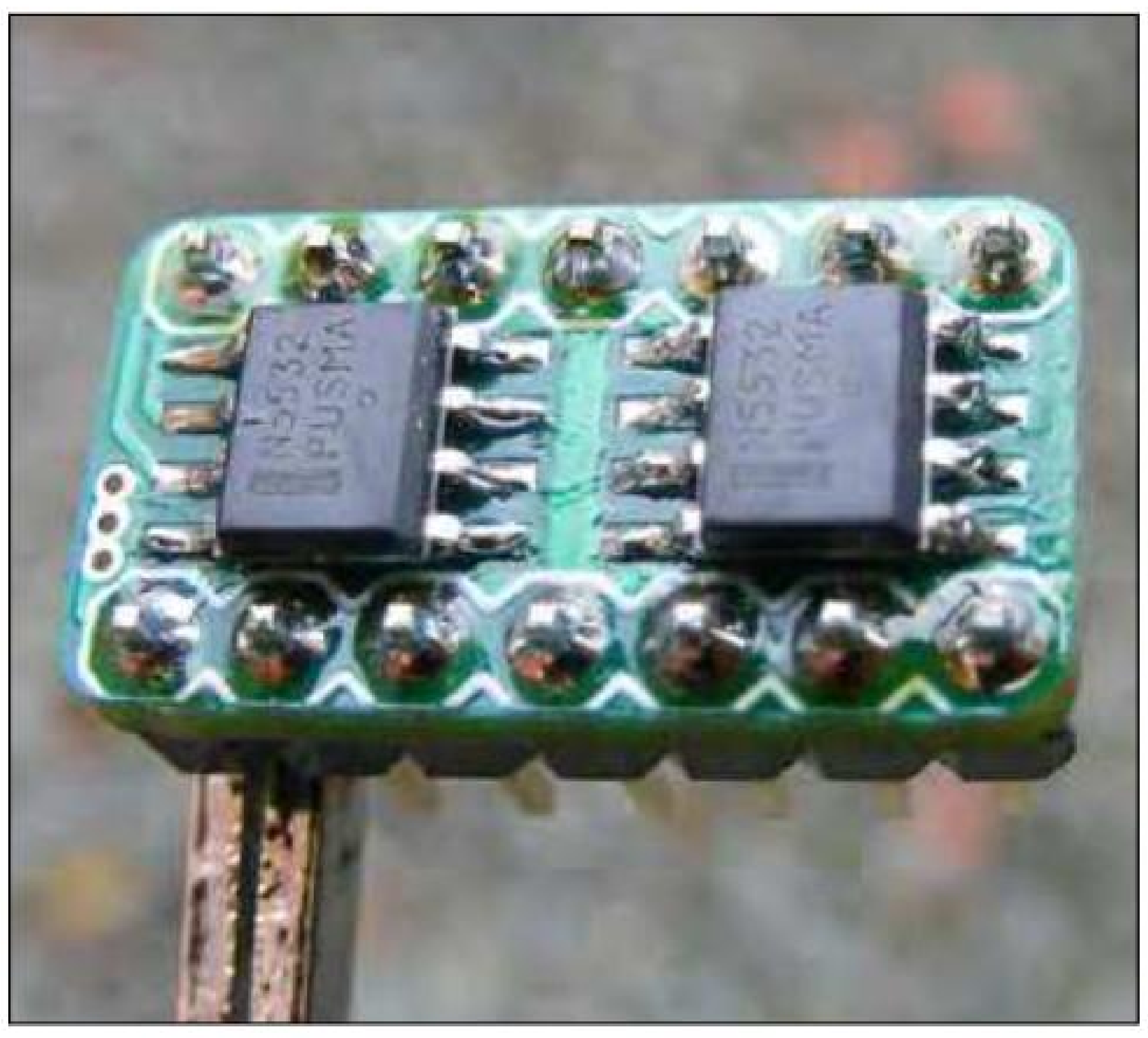


Fig.5. SMD dual-to-quad DIL adaptor close-up. These are dual NE5532s – note that the pin 1 end is identified with a bar.

these resemble the TL072 and can be satisfactorily replaced with the NJM8087 (maximum supply voltage ±16V).

Practical adaptor – quad devices

If you want to replace an old quad '741-style' device, such as the LM324, then a two-times-dual-to-quad adaptor board, which simply plugs into the original 14 pin DIL socket, is the solution. Its overlay is shown in Fig.2. An assembled unit is shown in Fig.3, and it is shown installed in an Audio Developments broadcast mixer channel in Fig.4.

It produced a marked improvement in the signal-to-noise ratio of the mixer. When all the op amps were replaced with 5532s the hiss dropped 12dB and the distortion dropped to a tenth at 0.002%. However, there were some op amp upgrade side effects, mainly high-frequency instability. This was fixed by putting 47pF capacitors on the feedback resistors and several 100nF capacitors across the power rails from positive to negative. Also, the power consumption for each channel tripled from 12 to 36mA using the current-hungry 5532s.

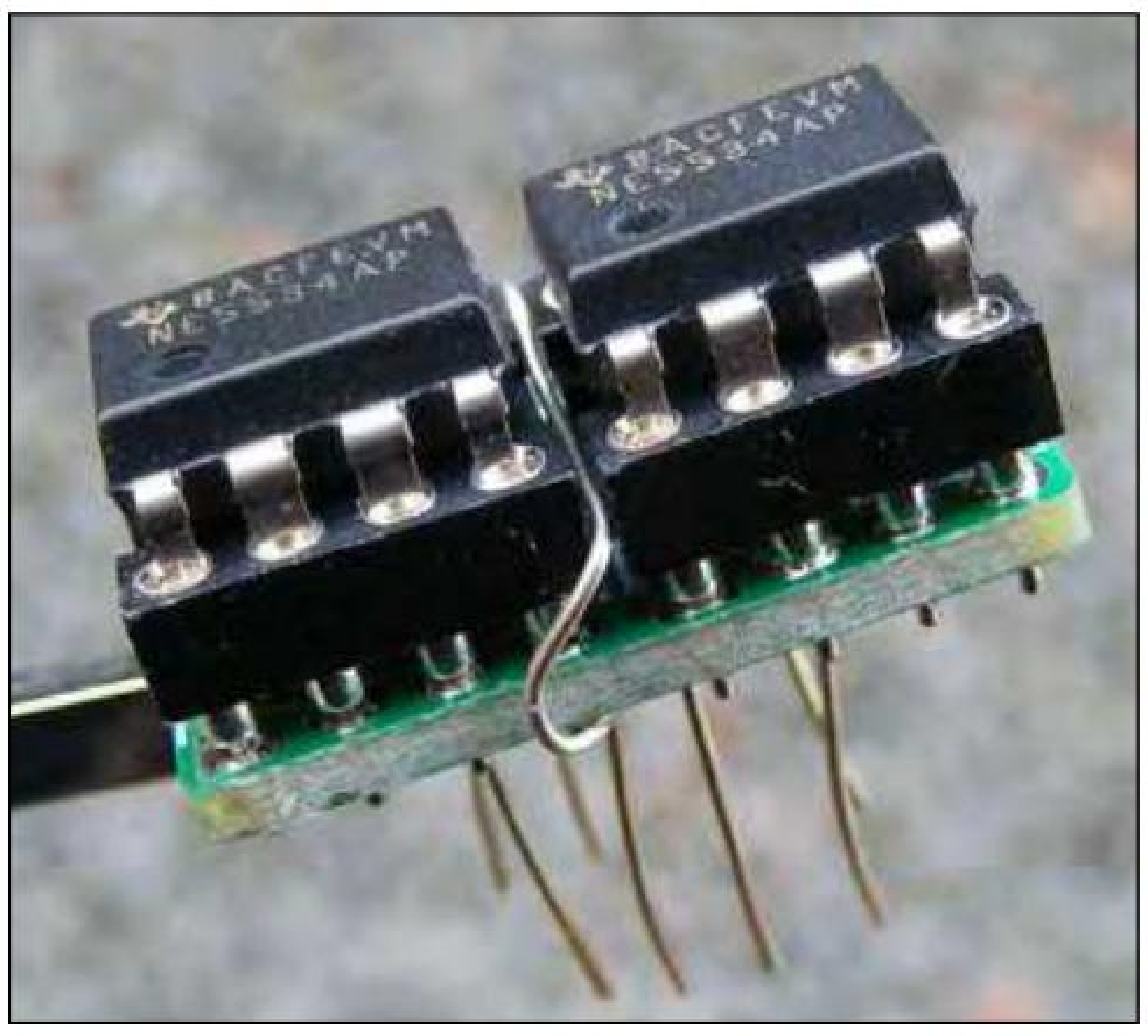


Fig.8. Two-singles-to-dual op amp adaptor board.

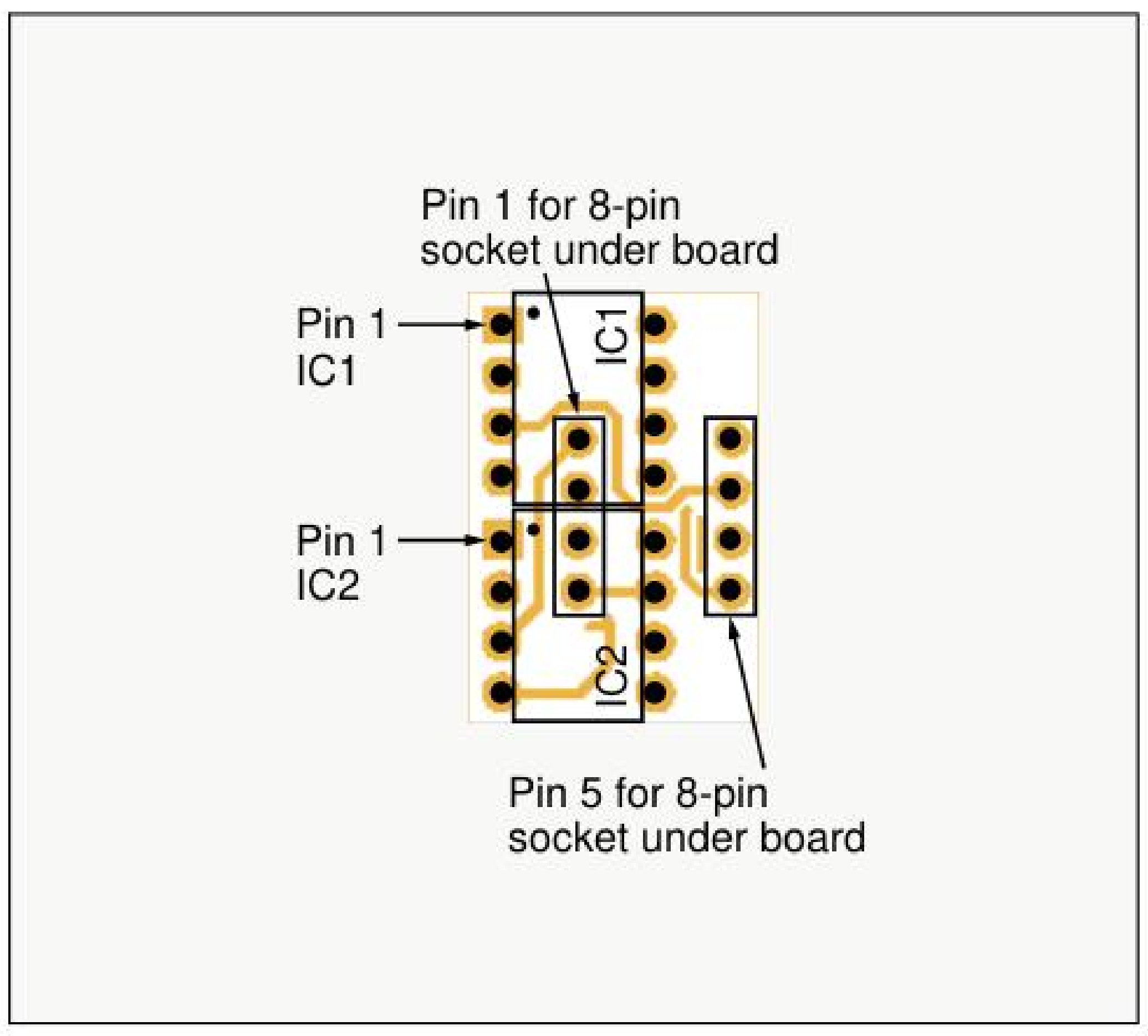

Pin 1 for 8-pin socket under board
Pin 1 IC1
IC1
Pin 1 IC2
IC2
Pin 5 for 8-pin socket under board

Fig.9. Overlay for the two-singles-to-dual adaptor board.

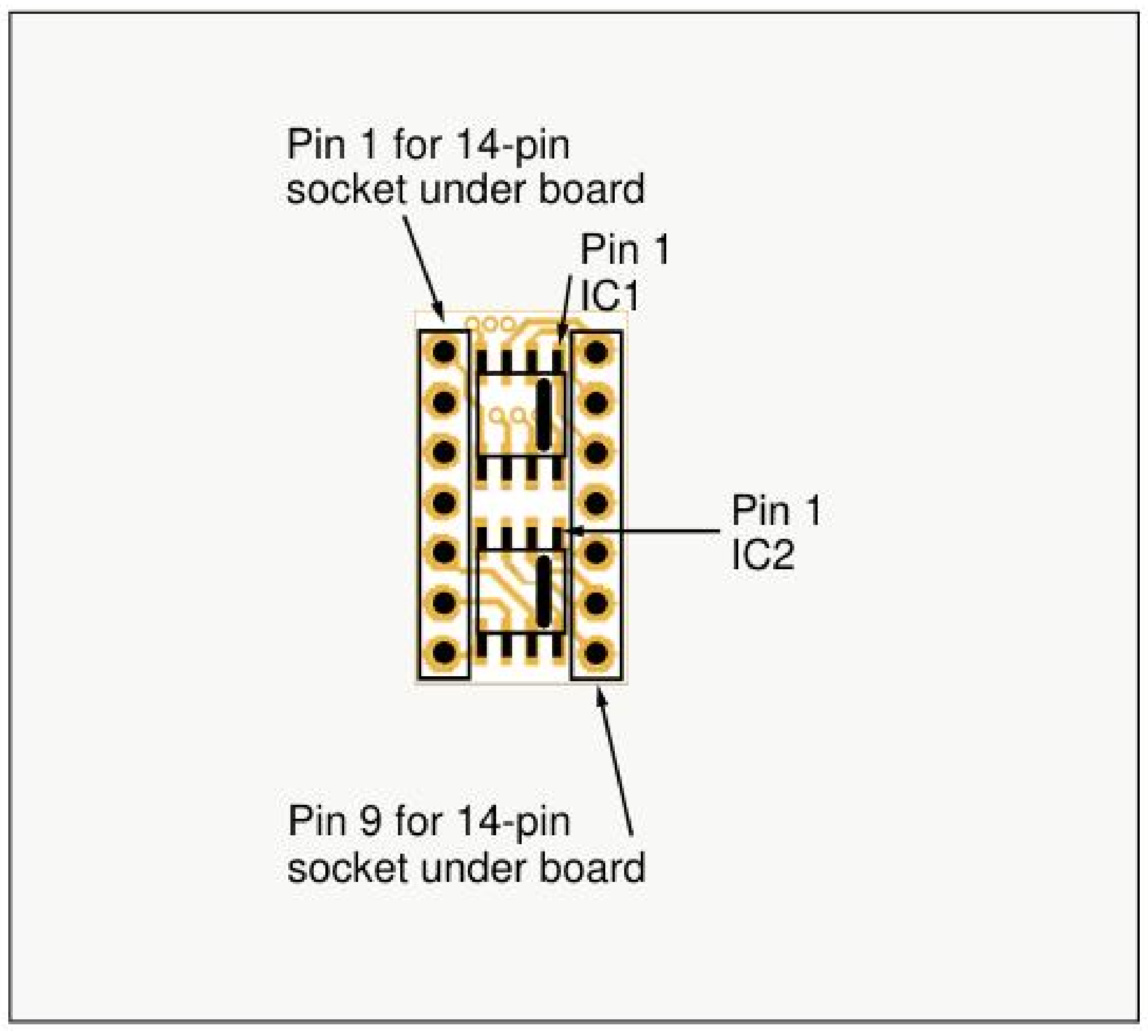

Pin 1 for 14-pin socket under board
Pin 1 IC1
Pin 1 IC2
Pin 9 for 14-pin socket under board

Fig.6. Component overlay of the SMD version of the two-duals-to-quad DIL socket adaptor.

Quad SMD

I've also created an SMD version of this adaptor, which is smaller and easier to install, as shown in Fig.5. The overlay is shown in Fig.6 and its mixer installation in Fig.7. Using these boards, I was able to compare the OnSemi SMD versions with their Texas DIL counterparts. Strangely the distortion of the SMD parts was 30% higher. I suspect the die may have been shrunk, a common cost-cutting procedure.

If you are interested in comparing op amp distortion figures, Swiss audio engineer Samuel Groner plotted the results for dozens of devices in his epic analysis at: **https://bit.ly/pe-may23-ao**

Two-singles-to-dual adaptor

In Fig.8 you can see the little board for adapting a dual op amp to two single op amp ICs. This is a handy option for many applications – for example, if you wanted to replace a dual NE5532 with two NE5534As, which would provide lower noise, lower distortion and double the dissipation it can handle. Do remember that when using the NE5534A with gains below five then it's necessary to add compensation capacitors across pins 5 and 8.

This board is also useful for exploiting the full ±24V rail voltage rating of the single-pack OPA604 because the dual version, the OPA2604, has recently been downrated by Texas to ±20V.

The overlay for this design is shown in Fig.9, and you can see it in action in Fig.10, installed in the dual RIAA board described last month. Note the use of solid wire (25 SWG) to raise the adaptor board above neighbouring capacitors. The SMD version is shown in Fig.11 and Fig.12.

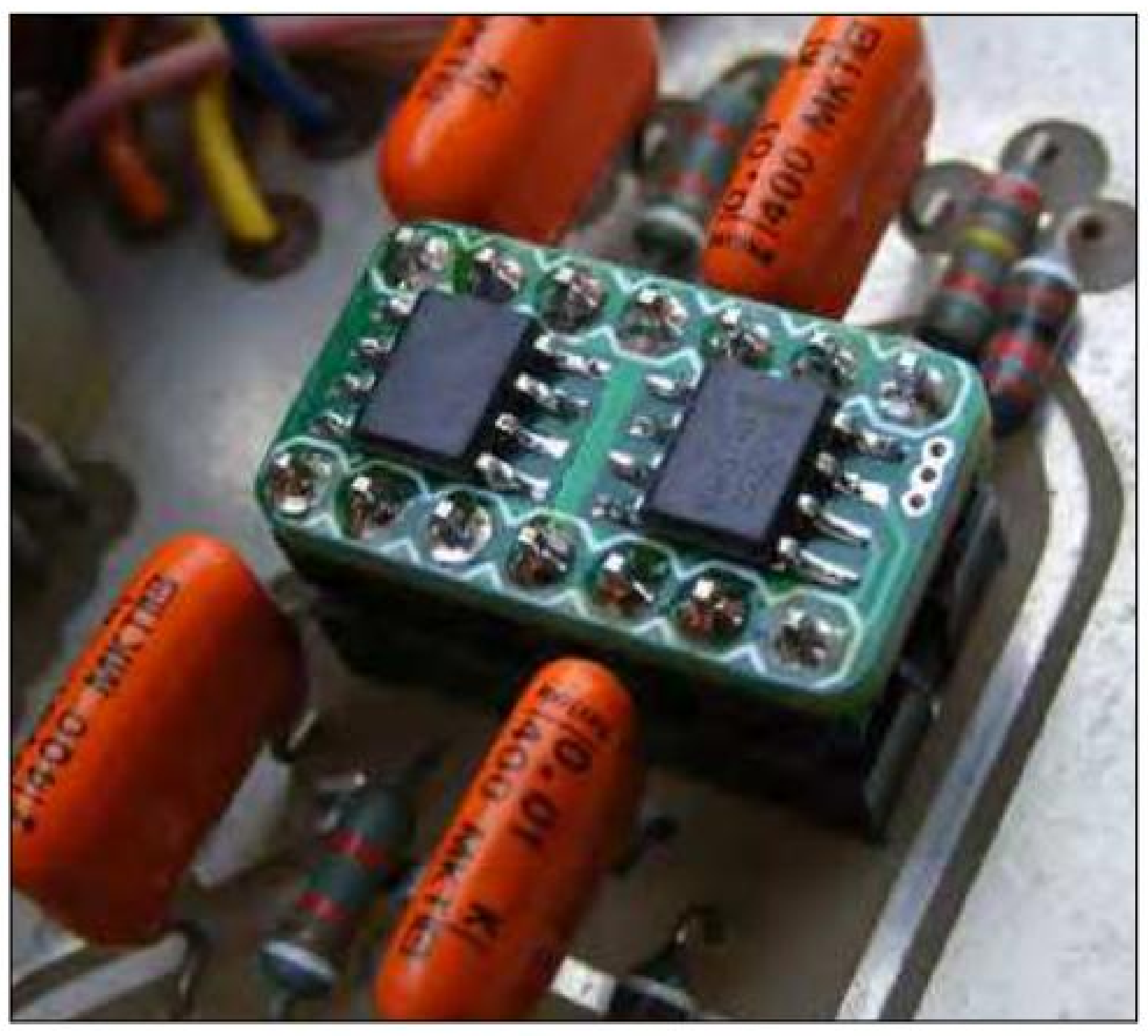


Fig.7. Surface-mount version of the quad adaptor shown in a mixer. SMD versions are smaller, so they are often easier to fit.

Soldering the adaptors

Standard square-pin 0.1-inch headers (eg, BKL from Rapid, part 50-8086) act as the 'plugs' into normal leaf spring IC sockets. If turned-pin sockets are used on the 'motherboard' then you have to use round-pin headers on the adaptor

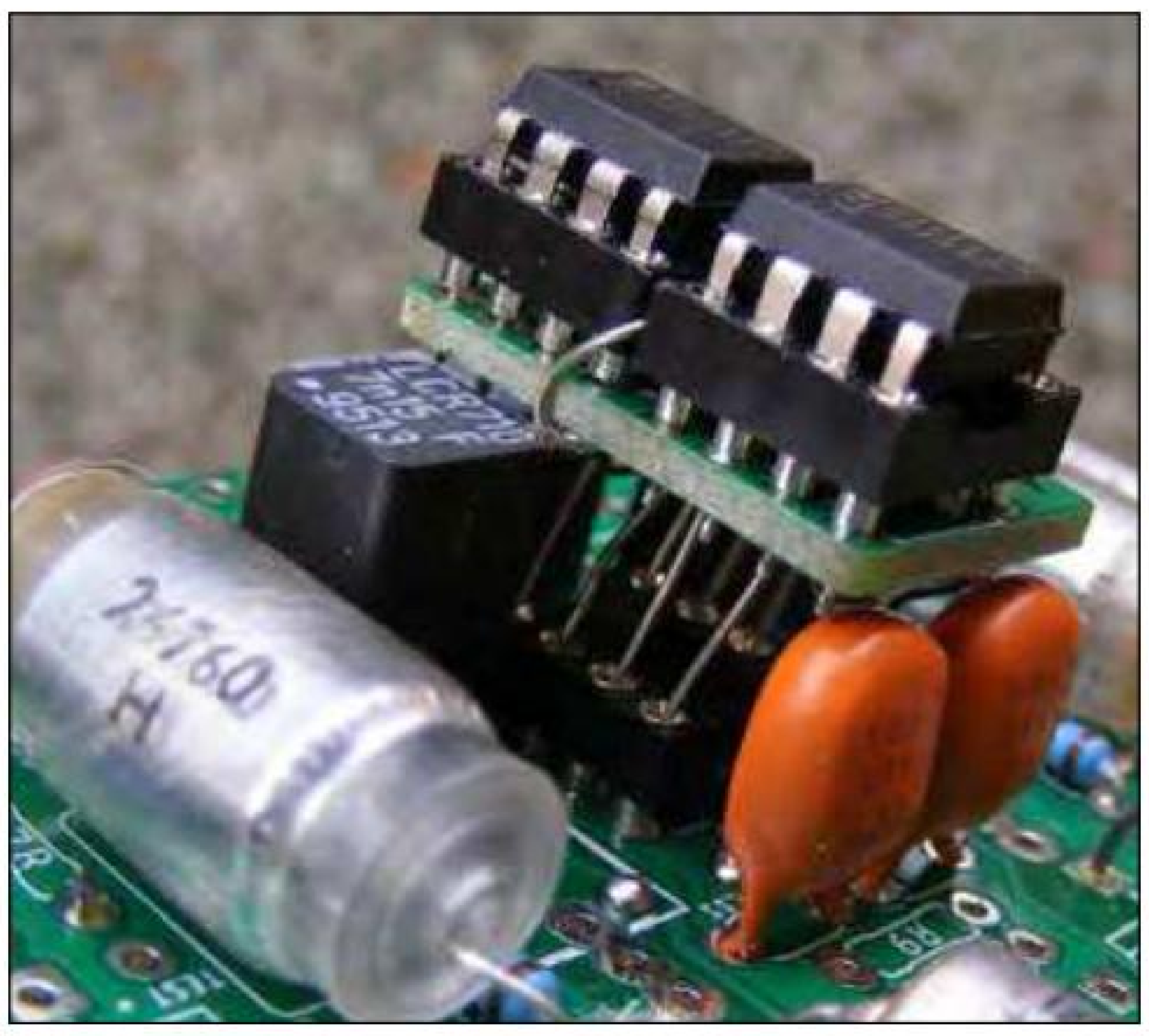


Fig.10. Two-singles-to-dual adaptor board installed in an RIAA preamplifier. Note the use of tinned copper wire to plug into turned-pin sockets.

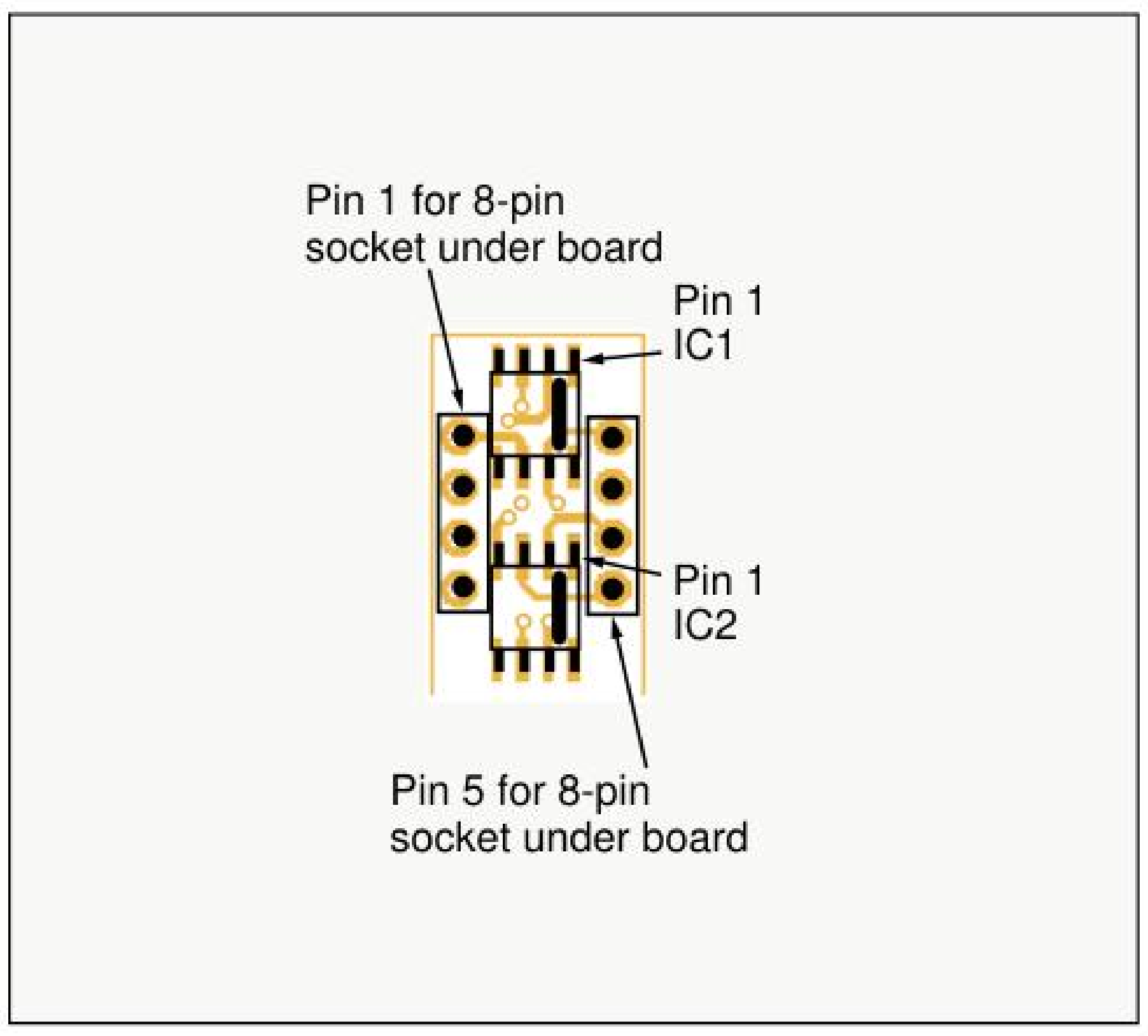

Pin 1 for 8-pin socket under board
Pin 1 IC1
Pin 1 IC2
Pin 5 for 8-pin socket under board

Fig.11. Component overlay of the SMD version of the two-singles-to-dual adaptor board.

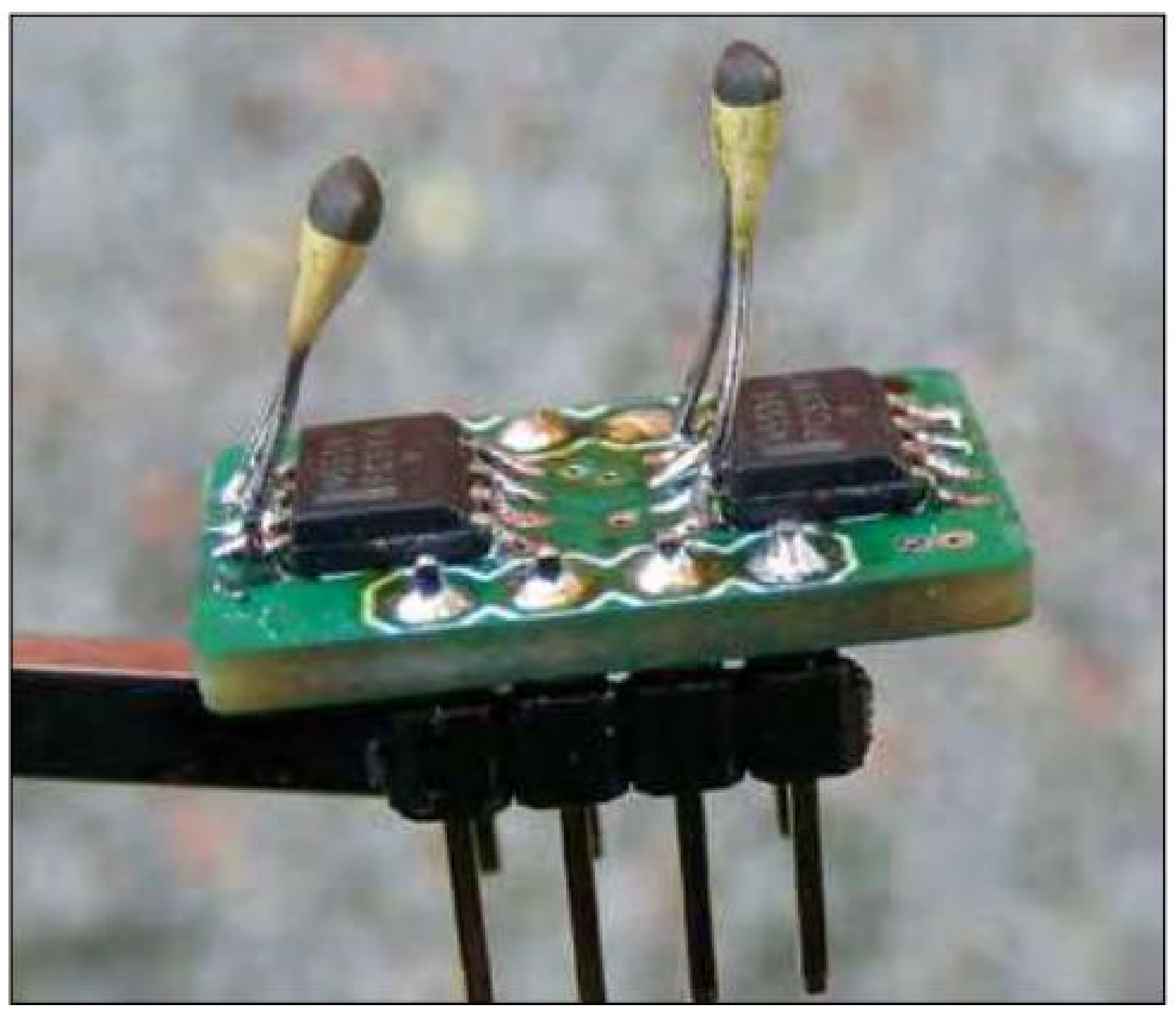


Fig.12. Assembled SMD version of the two-singles-to-dual adaptor board. Compensation capacitors for NE5534 op amps that have been added. Sometimes a power supply decoupling capacitor should be soldered on as well.

board (eg, TruConnect from Rapid, part 22-1704). These are also available from Tayda (part number A-4662). I had run out of round-pin stock, which is partly why I had to use the 25 SWG tinned copper wire mentioned above. It fits well, but can bend easily.

There is a logical order for soldering the adaptors, such as soldering the headers before soldering the IC sockets on top (see Fig.13). In Fig.2, you can see pins 1 to 7 could end up under the op amps and be very difficult to solder with bits of plastic blocking the soldering iron tip.

Sourcing the boards

All four adaptor boards are available in packs of five from the *PE PCB Service*.

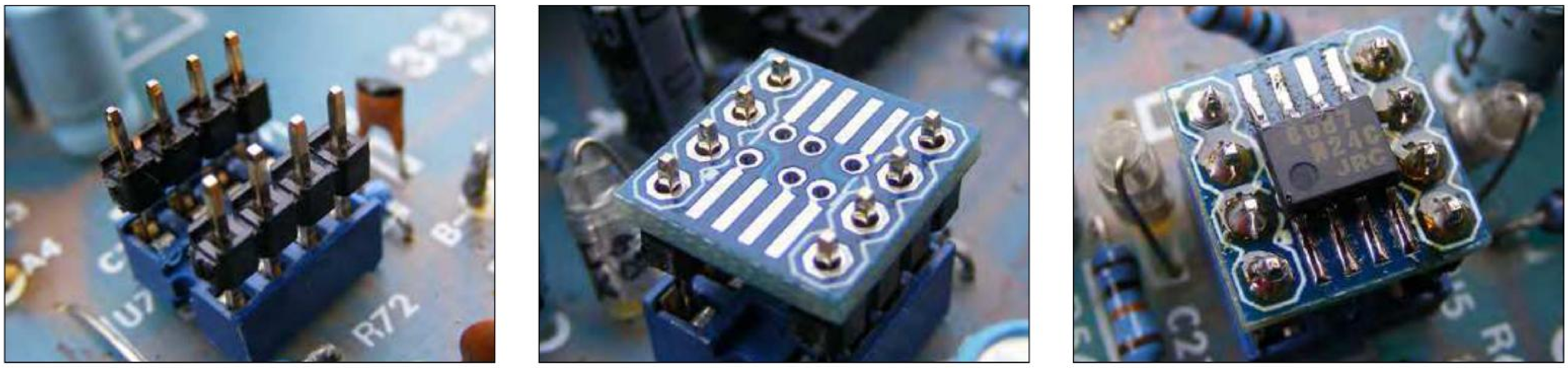


Fig.13. The best way to solder pins to an adaptor board is to first put them in a socket on the 'motherboard'. This holds the pins in alignment and provides a stable platform for soldering the adaptor and op amp(s). Note the 8087, which replaced a TL072 in a mixer channel.

Desoldering component puller

Many electronic engineers make their own little jigs and tools to deal with the odd jobs that come their way. As somebody who deals with studio equipment, I have a vast junk box full of control knobs of all different sizes and shaft diameters. A lot of these are collet knobs, which have a clamping system similar to a drill chuck. These are very useful for holding things such as 3mm drills for stripboard cutting and the de-soldering aid described here.

When the curtain twitcher next door died, her hideous net curtains were thrown into a skip. I found a use for the plastic-coated coiled-spring steel wire used to hold them up (see Fig.1). It's 4mm diameter, so fits perfectly into a standard 4mm Sifam S15 collet knob, as shown in Fig.2. The wire is coated with a plastic sheath which should be peeled off to get a good fit in the knob.

Cut about 45mm of wire, then fashion a hook on the end for inserting under a component lead-out (Fig.3). Don't use your precision Lindstrom side cutters for this job; a tough old electrician's pair is needed. The tool is made short so it can be pulled against the board using one hand with the soldered joint being heated underneath at the same time, as illustrated in Fig.4. The beauty of this technique is that only two hands are needed, and it stops you getting burnt fingers.

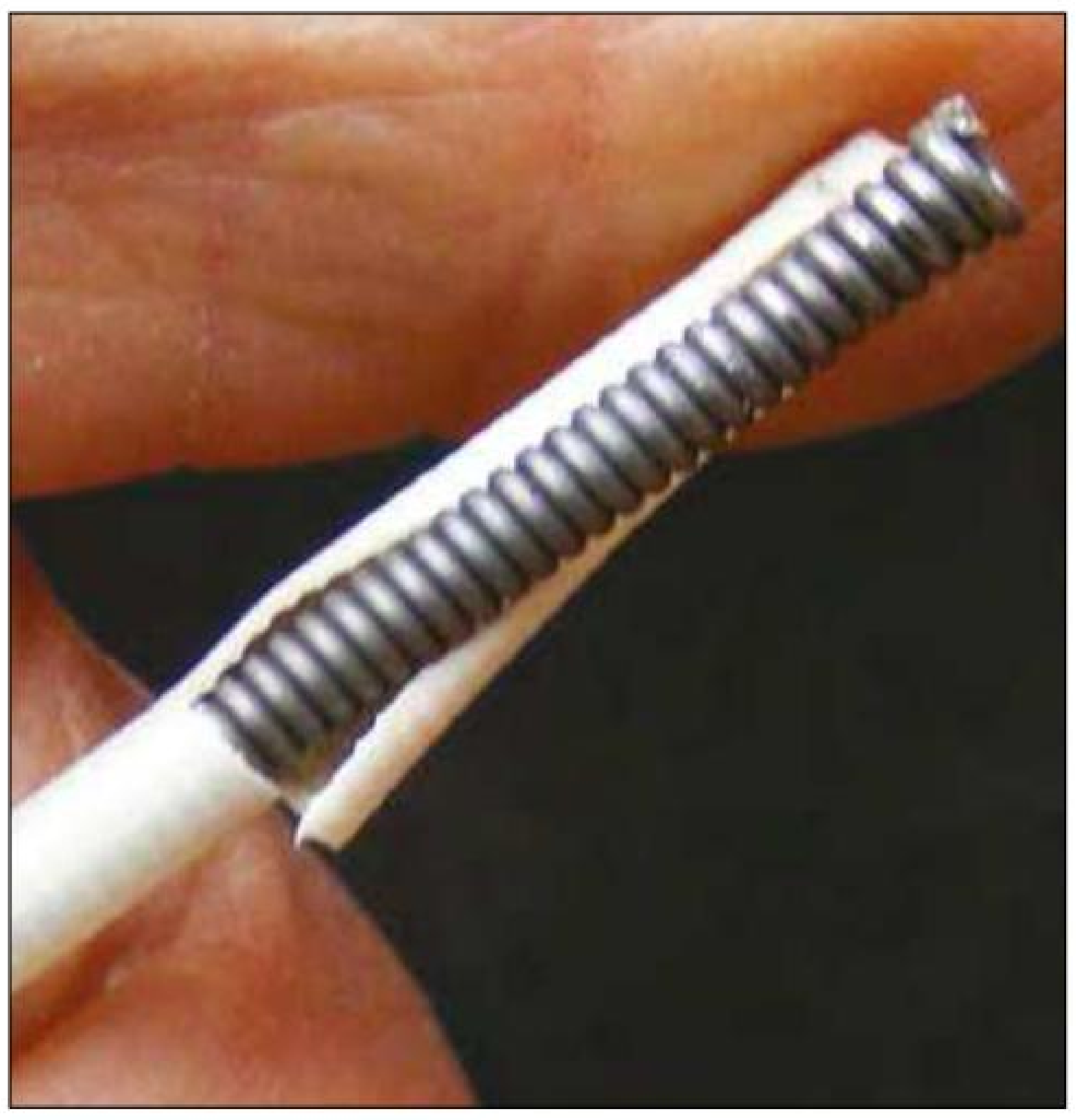


Fig.1. Always check skips! This net curtain wire is useful for all sorts of jobs – it's tough and springy.

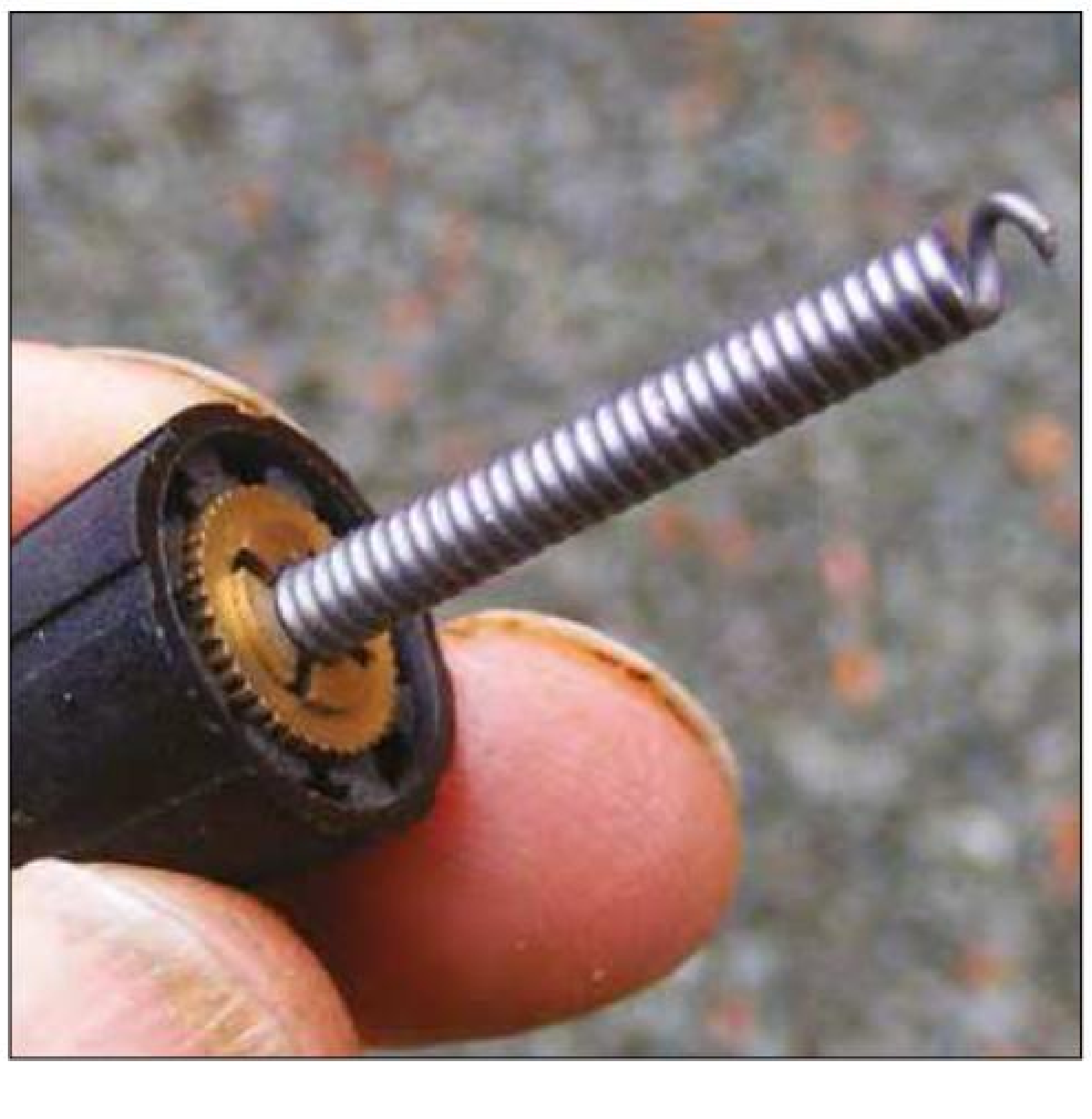


Fig.2. A 4mm collet knob is attached to the stripped net curtain wire.

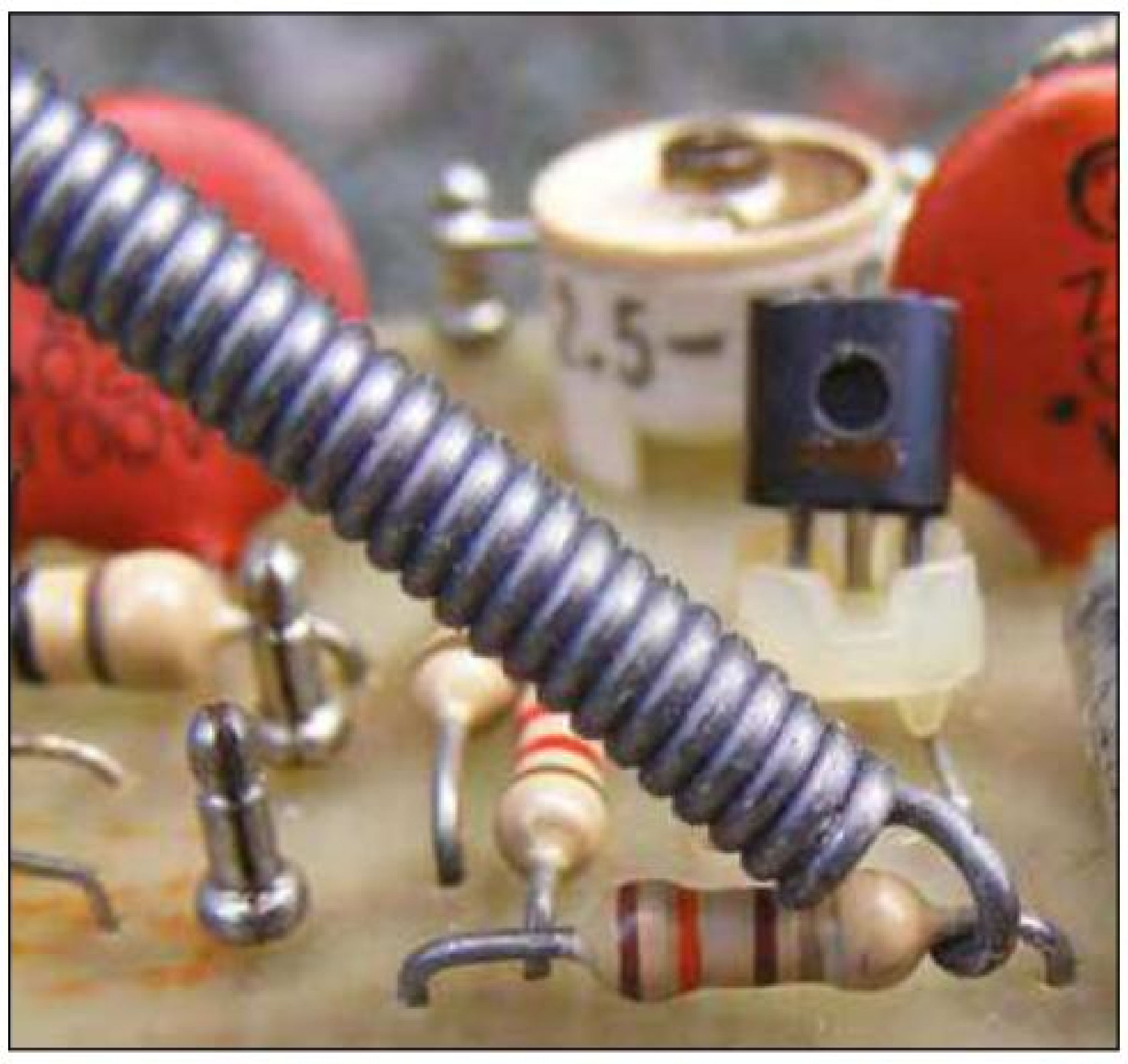


Fig.3. Close-up of the hook.

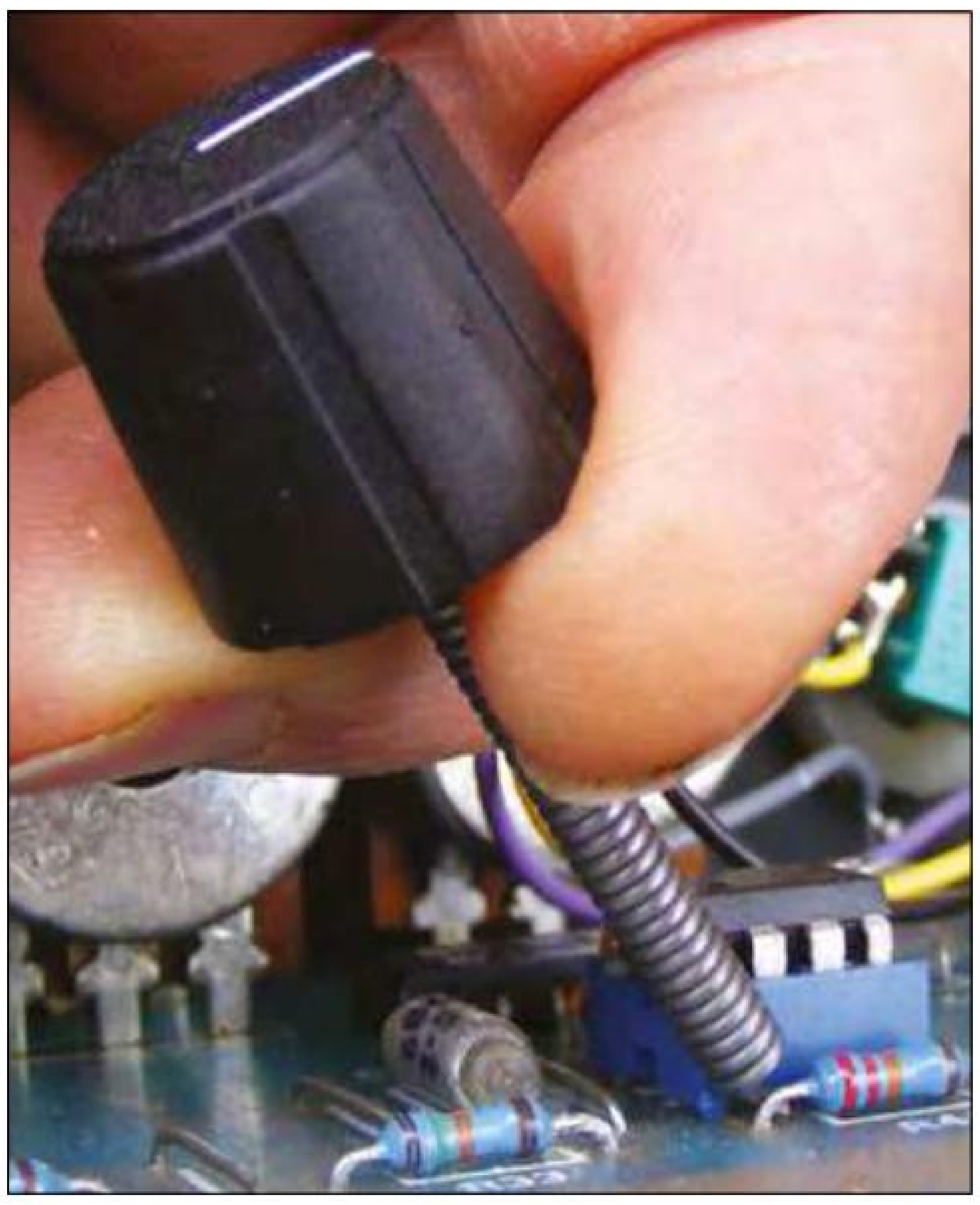
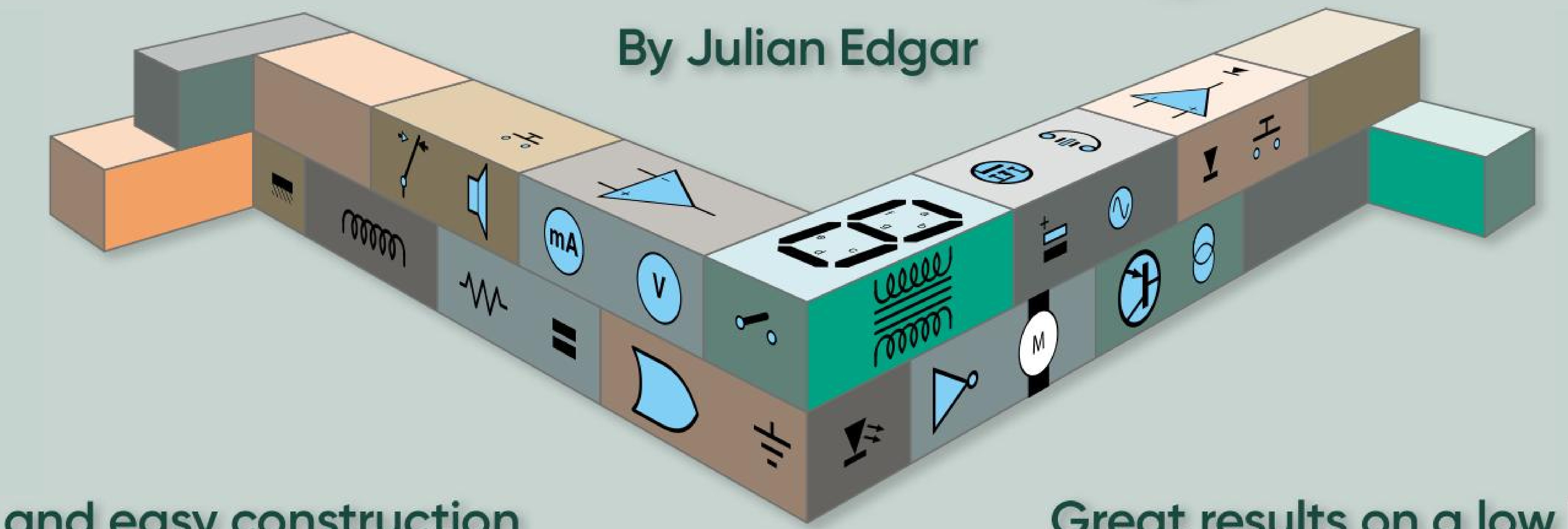


Fig.4. It's easy to pull the resistor out of the board with one hand, leaving the other hand free for the soldering iron. (I'm happy to supply knobs, curtain wire and even completed tools.)

Electronic Building Blocks

By Julian Edgar



Quick and easy construction

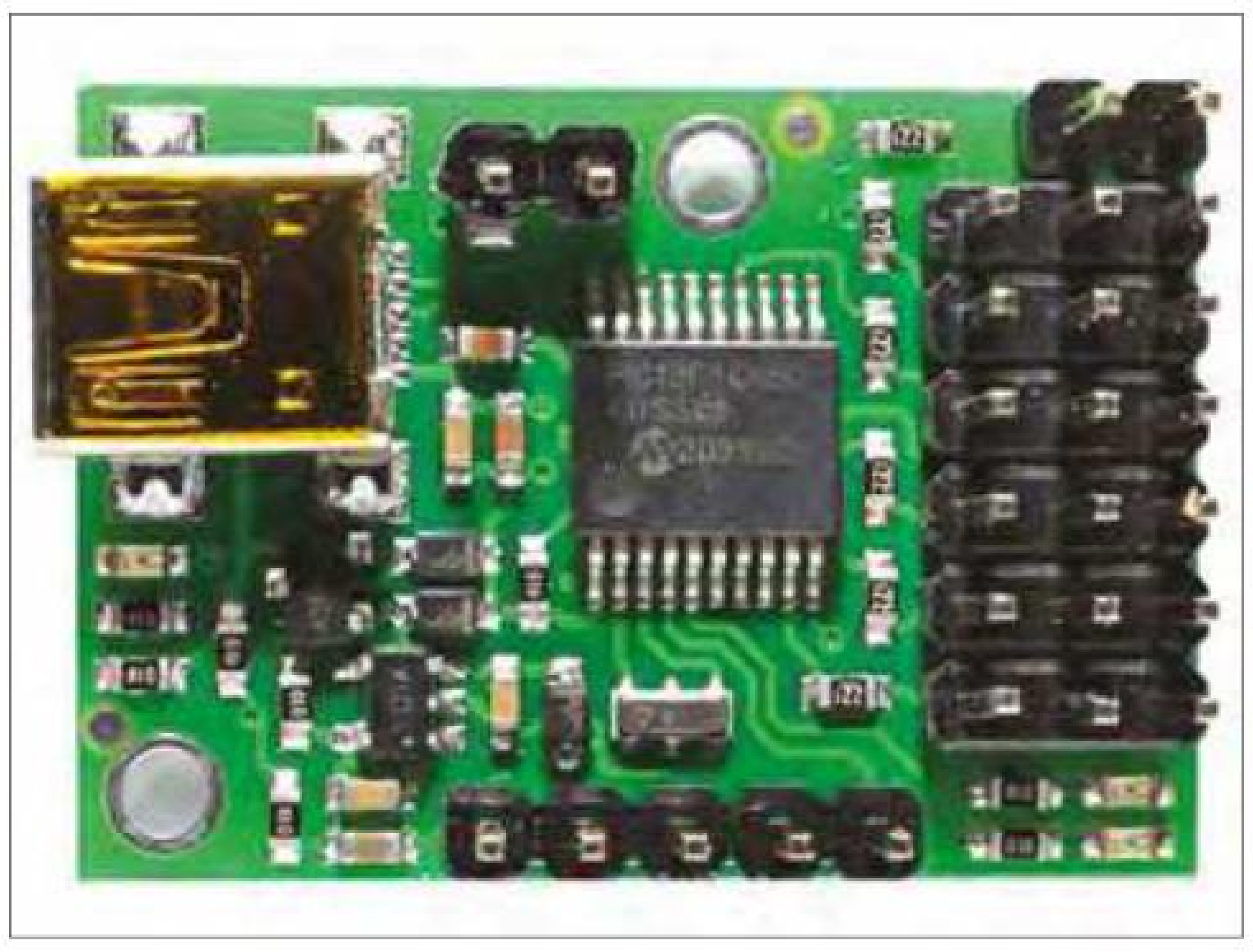
Great results on a low budget

Controlling RC servos with the Pololu Micro Maestro

Quick and simple programming for automatic servo movements, or manual control with a pot or switch

In previous articles, we've looked at selecting actuators (*PE*, October/November 2022); controlling stepper motors using an eBay pushbutton-programmable standalone module (*PE*, December 2021); and controlling linear actuators using the Pololu Jrk 21v3 PC-programmable module (*PE*, June/July 2022). In both the linear actuator and stepper motor articles, set-up and wiring were straightforward, putting control of these actuators into the hands of people who may not want to learn to code.

This month, we look at the Pololu Micro Maestro board, a PC programmable device than can simultaneously control up to six RC servos. Again, we're going to take the simplest approach: using a pot (a manual control knob) or a switch to control servo position. However, in addition, we're also going to look at how a sequence of instructions can be used to automatically cycle the servos through a series of movements.



The Pololu Micro Maestro board is a tiny – just 28 x 22mm and weighing 3g – but it can control up to 6 RC servos. The included software gives full control over servo position, and maximum servo speed and acceleration.

Pololu Micro Maestro

The Pololu Micro Maestro is a tiny (just 28 x 22mm), light weight (3g) board that packs a lot of capability into a small footprint. All connections are by header pins – there are no screw terminals. It costs around £40 and is available from a wide range of sources.

Part of a family of different Maestro servo motors controllers, the Maestro has six channels (other Maestros have up to 24 channels). They're called 'channels' rather than 'outputs' because each channel on the Micro can be used as an RC servo drive or as an analogue input channel. The channel function is selected in the PC configuration software – more on the software in a moment.

Each servo control channel can be set for maximum speed and acceleration, and if an error is detected, channels can be configured to go to a specified servo position or turn off. The servo(s) can be controlled from a PC via a USB cable, by a serial connection or by an internal program (called a script) that also allows user control via external pots or switches. It's the 'script' approach that we will be covering here.

Initial set-up and testing

To get the Micro Maestro up and running, you will need a USB mini-B cable (not included), an RC servo and a power supply suitable for the operating voltage of the servo (4.8 – 6V). The power supply connection for the servos is separate to the power supply for the Micro Maestro, but since the Maestro can work on 5-16V, the servo power supply can also supply power to the board. Alternatively, the board can be powered by the USB connection and the servos powered by a power supply (or batteries, of course). The servo power supply connection (power and ground) makes available power to all the servo channels, so only one pair of connections is needed. See Fig.1 for these connections.

With 4.8-6V connected to the module's servo power feed, the next step is to connect a servo itself. The three-pin female plug provided on RC servos plugs straight into the board header pins at any of the six channel positions (labelled 0-5). However – and this is important – the servo must be connected with the correct polarity. Servo wiring is typically:

Ground	Power	Signal
black	red	white
brown	red	orange
black	red	blue

RC servos are versatile controllable actuators that are ideal for operating arms and legs in hobby robots, moving items in animated model layouts, opening and closing vents and many other uses. They're low in cost and widely available.

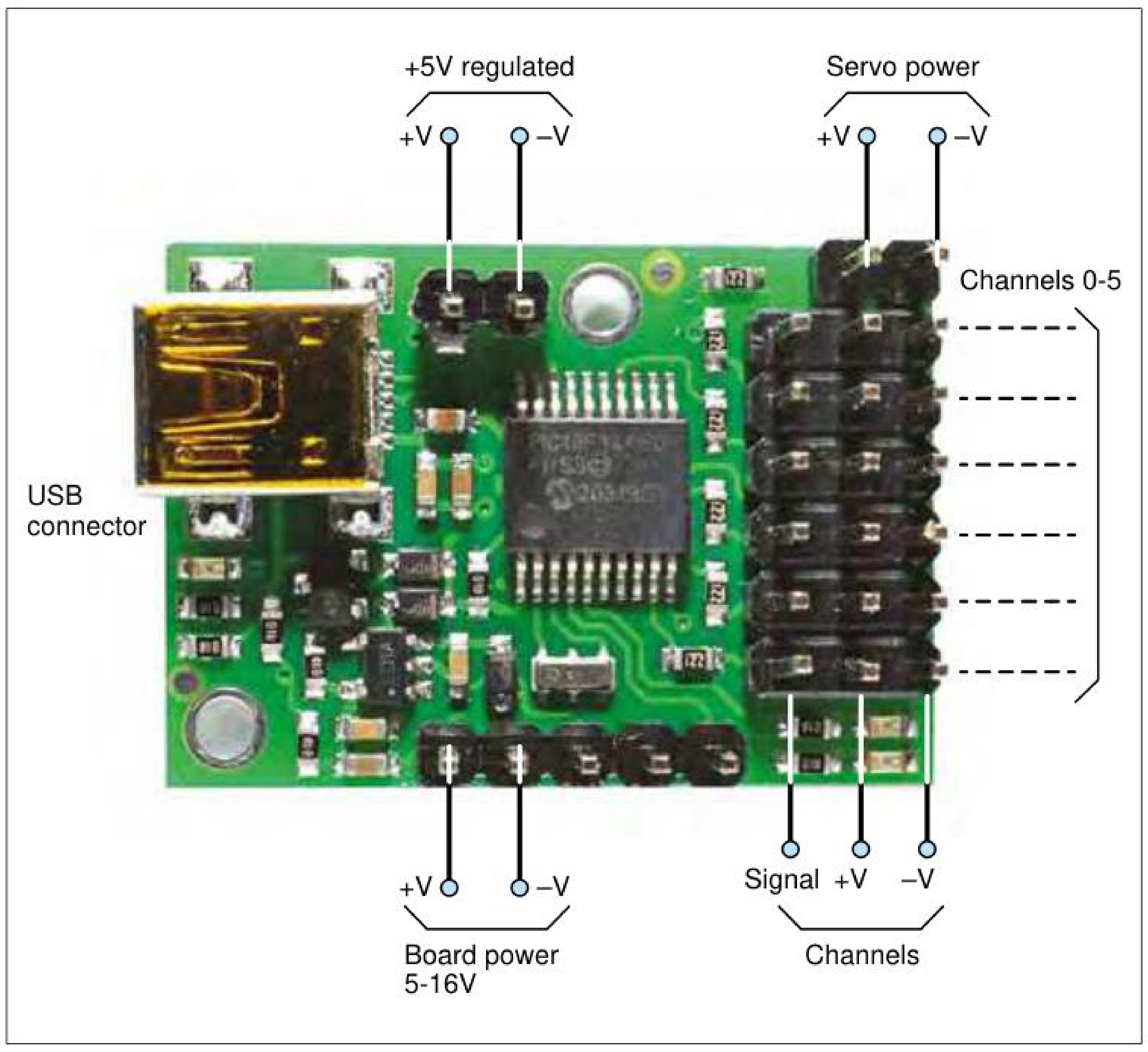

+5V regulated
+V
–V
Servo power
+V
–V
Channels 0-5
USB connector
+V
–V
Board power 5-16V
Signal
+V
–V
Channels

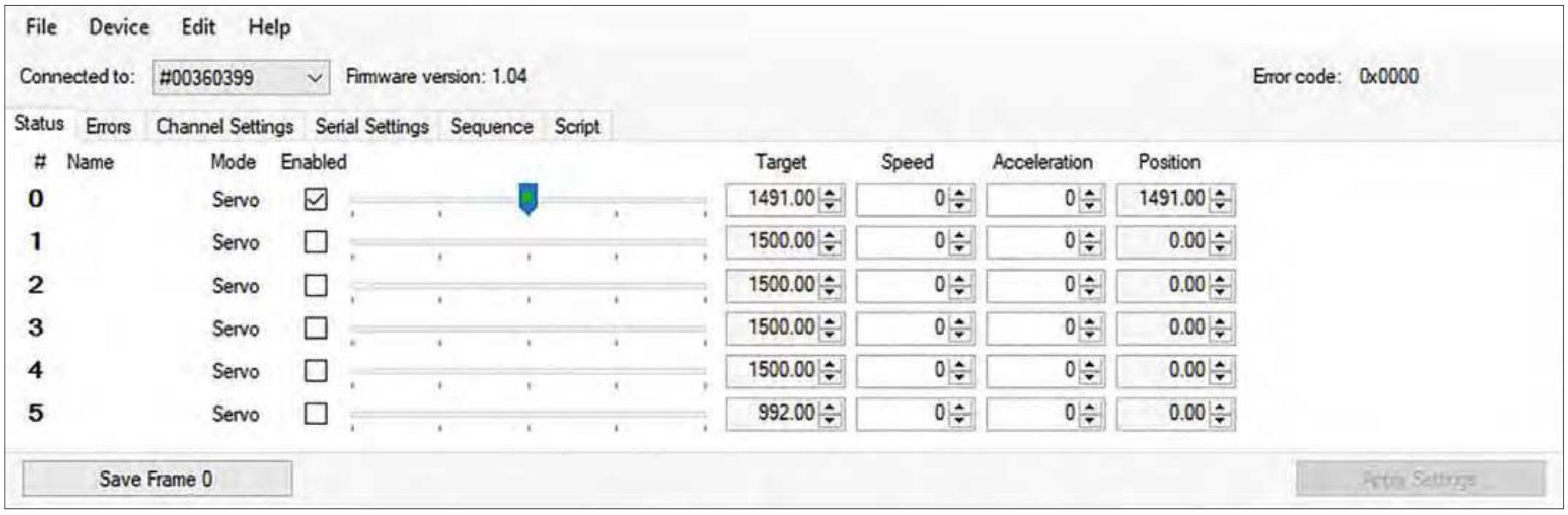
Fig.1. These are the connections that you'll need to make to do all that is covered in this article. The two-pin header for the regulated 5V supply and associated ground connection will need to be provided and soldered into place – it's not included.

The table is read from left to right – that is, one common plug is black-red-white, for example. See Fig.1 or the underside of the Maestro for these servo connections.

The next step is to load the Windows drivers and software on to the PC. This is best done by clicking on the download link in the excellent Micro Maestro PDF user's guide. (The guide is also downloadable from Pololu and its dealers.) There is a large section in the manual on installing the software, but with Windows 10 Pro, I just followed the on-screen prompts and had no difficulties.

Now it's time to control the servo. With the Maestro connected to the PC, servo power switched on and the servo connected, open the software. Software connection with the module is established in the *Connected to* pull-down. Once the PC is talking to the Maestro, you can then tick the box to Enable the channel to which you wired the servo. Then, without doing anything further, when you move the relevant on-screen slider back and forth, the servo will rotate accordingly – see: Fig.2.

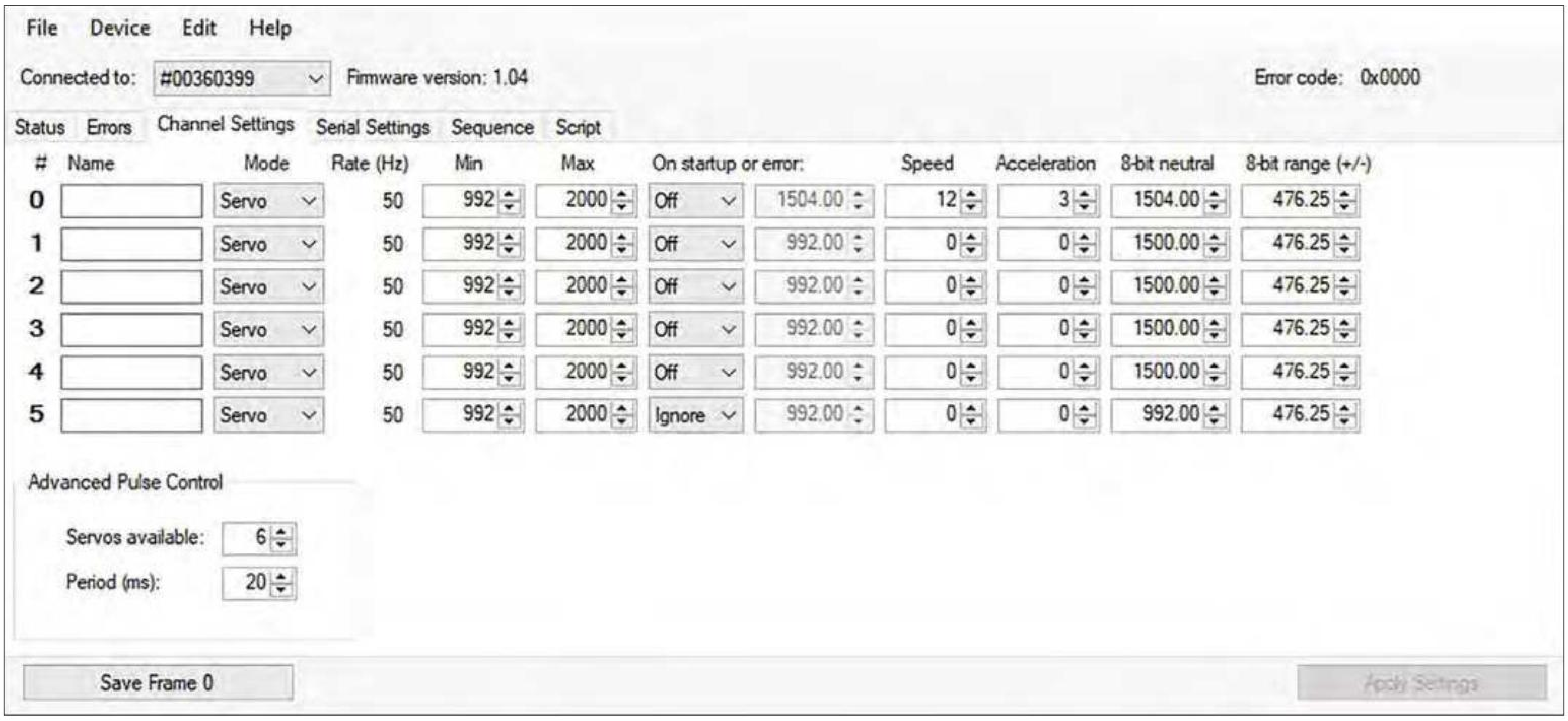
Note that quick movements of the slider will give equally quick movements of the servo. To produce smoother movements, change the value in the Speed box. For example, setting this to '5' meant it took the test servo about 8 seconds to go from one extreme of movement to the other. In addition to maximum speed, you can also set maximum acceleration.


File
Device
Edit
Help
Status
Errors
Channel Settings
Serial Settings
Sequence
Script
Save Frame 0
Apply Settings

Connected to: #00360399
Firmware version: 1.04
Error code: 0x0000

#	Name	Mode	Enabled	Target	Speed	Acceleration	Position
0		Servo	☑	1491.00	0	0	1491.00
1		Servo	☐	1500.00	0	0	0.00
2		Servo	☐	1500.00	0	0	0.00
3		Servo	☐	1500.00	0	0	0.00
4		Servo	☐	1500.00	0	0	0.00
5		Servo	☐	992.00	0	0	0.00

Fig.2. The *Status* tab allows you to easily control the movement of the servo by dragging the slider back and forth. Five different servos can be controlled but here only one output channel has been activated.


File
Device
Edit
Help
Status
Errors
Channel Settings
Serial Settings
Sequence
Script
Save Frame 0
Apply Settings

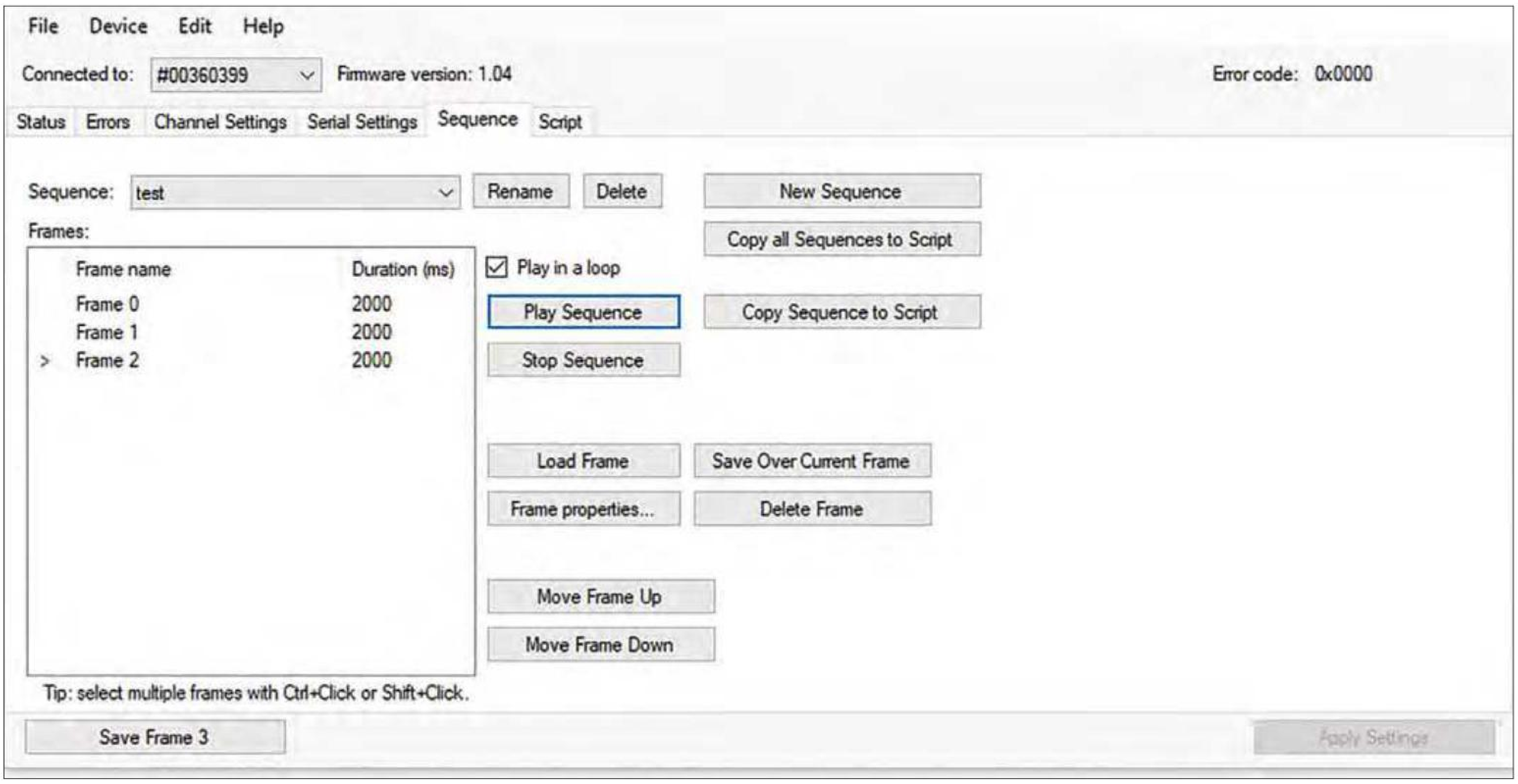
Connected to: #00360399
Firmware version: 1.04
Error code: 0x0000

#	Name	Mode	Rate (Hz)	Min	Max	On startup or error:		Speed	Acceleration	8-bit neutral	8-bit range (+/-)
0		Servo	50	992	2000	Off	1504.00	12	3	1504.00	476.25
1		Servo	50	992	2000	Off	992.00	0	0	1500.00	476.25
2		Servo	50	992	2000	Off	992.00	0	0	1500.00	476.25
3		Servo	50	992	2000	Off	992.00	0	0	1500.00	476.25
4		Servo	50	992	2000	Off	992.00	0	0	1500.00	476.25
5		Servo	50	992	2000	Ignore	992.00	0	0	992.00	476.25

Advanced Pulse Control

Servos available: 6
Period (ms): 20

Fig.3. In *Channel Settings* the speed, acceleration, minimum and maximum positions of each servo can be set. Each channel can also be named (not done here).


File
Device
Edit
Help
Status
Errors
Channel Settings
Serial Settings
Sequence
Script
Rename
Delete
New Sequence
Copy all Sequences to Script
Play Sequence
Copy Sequence to Script
Stop Sequence
Load Frame
Save Over Current Frame
Frame properties...
Delete Frame
Move Frame Up
Move Frame Down
Save Frame 3
Apply Settings

Connected to: #00360399
Firmware version: 1.04
Error code: 0x0000

Sequence: test

Frames:

	Frame name	Duration (ms)
	Frame 0	2000
	Frame 1	2000
>	Frame 2	2000

☑ Play in a loop

Tip: select multiple frames with Ctrl+Click or Shift+Click.

Fig.4. In the *Sequence* tab, the use of frames (think of them as movement steps) allows a sequence of movements to be developed and then uploaded to the module. It's a quick and easy process, especially for repetitive movements (like making a robot walk).

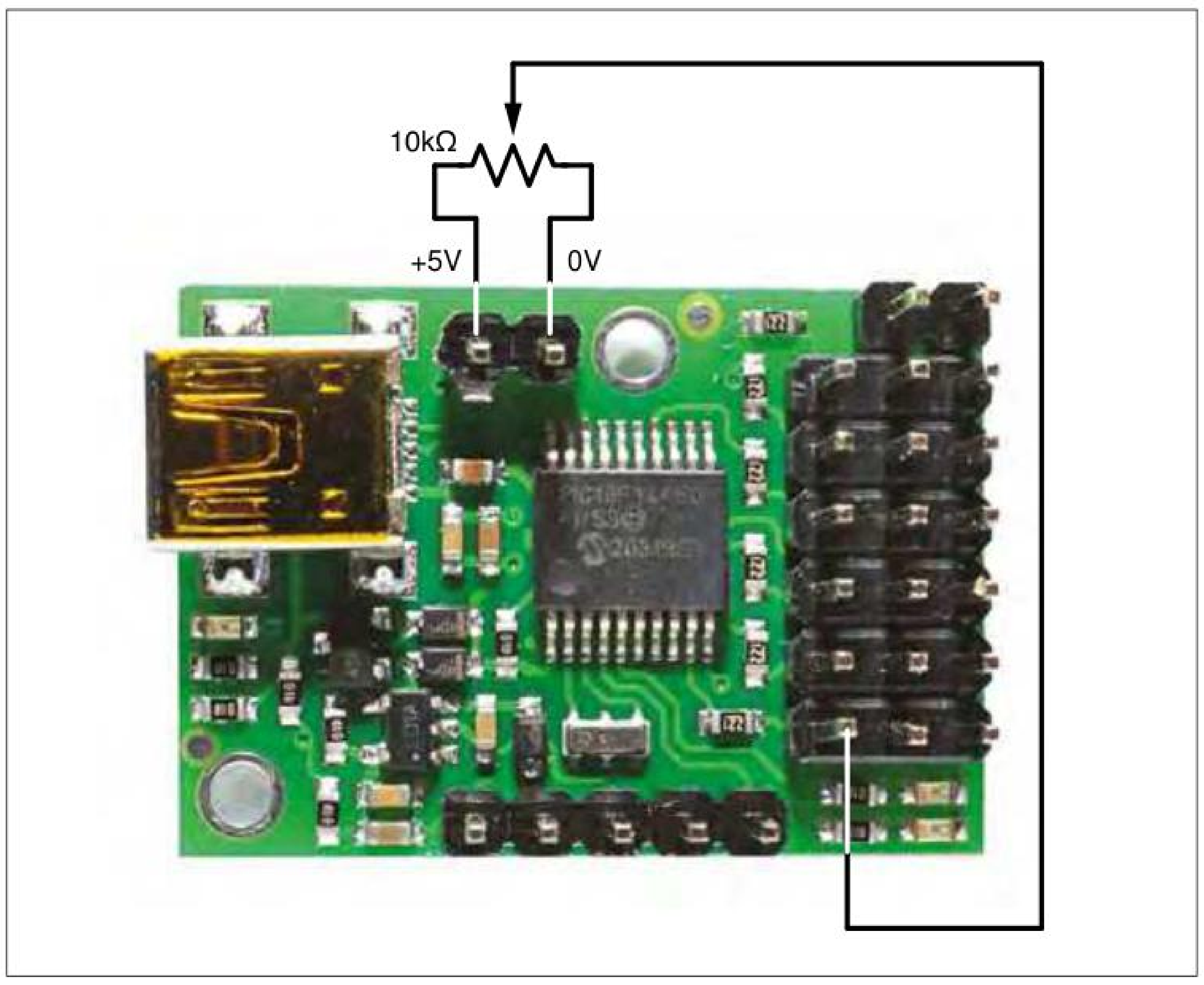
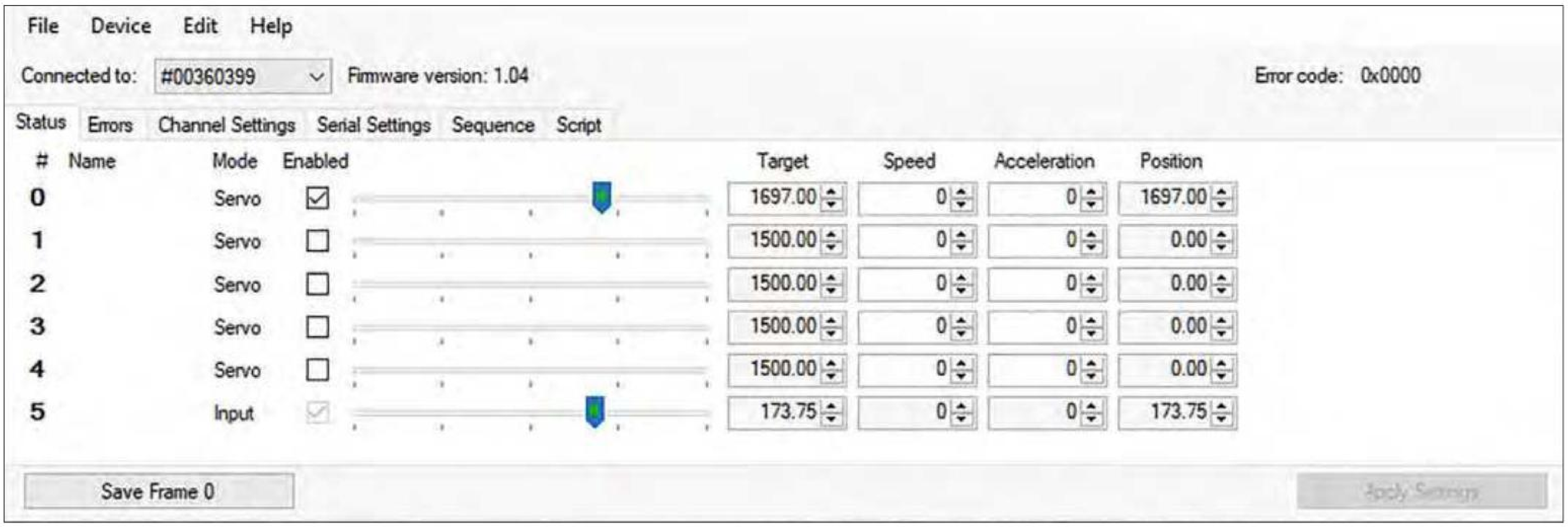


Fig.5. Using the regulated 5V and ground connections, a pot can be energised and its variable voltage output connected to a channel input. This allows manual control over the servo position.

By using a combination of these controls, you can have the servo smoothly accelerate to a set maximum speed, and then just as smoothly decelerate to a stop at the setpoint. These effects can be judged not only from the action of the observed servo, but also from watching the on-screen slider, where the setpoint is shown by a marker and the actual servo position by a dot.

Now open the *Channel Settings* tab. For each connected servo, the minimum and maximum rotational positions can be set. In this tab you can also set the servo behaviour on start-up or when an error is detected – *off*, *ignore* or *go to*, with the latter allowing the position to be specified. In this tab you can also see the *Speed* and *Acceleration* settings you've already configured, and you can name each channel as you wish. Note that any changes need to be uploaded to the Maestro by pressing *Apply Settings* – further details in Fig.3

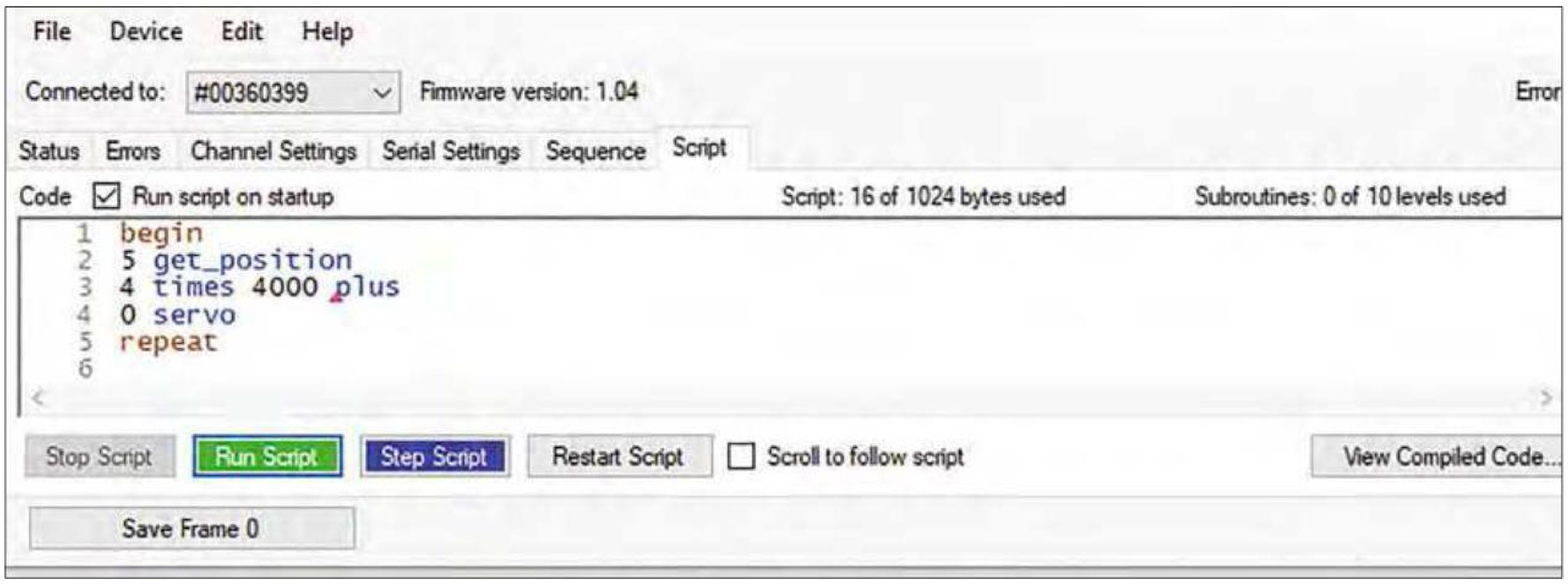
You might be wondering what units are used for the servo position. These are in microseconds (µs) pulse width – something that sounds odd until you realise that it is the pulse width of the signal that controls servo position. (See the breakout box for how an RC servo works.)


File
Device
Edit
Help
Status
Errors
Channel Settings
Serial Settings
Sequence
Script
Save Frame 0
Apply Settings

Connected to: #00360399
Firmware version: 1.04
Error code: 0x0000

#	Name	Mode	Enabled	Target	Speed	Acceleration	Position
0		Servo	☑	1697.00	0	0	1697.00
1		Servo	☐	1500.00	0	0	0.00
2		Servo	☐	1500.00	0	0	0.00
3		Servo	☐	1500.00	0	0	0.00
4		Servo	☐	1500.00	0	0	0.00
5		Input	☑	173.75	0	0	173.75

Fig.6. Here, Channel 5 has been altered in function to become an input. Rotation of the added pot moves the *Input* slider, so that it's easy to checking that the pot input is working.



Connected to: #00360399

Firmware version: 1.04

☑ Run script on startup

Script: 16 of 1024 bytes used

Subroutines: 0 of 10 levels used

☐ Scroll to follow script

```
begin
5 get_position
4 times 4000 plus
0 servo
repeat
```

Fig.7. This very simple program allows the external pot to control the movement of the servo. A switch can also be used with this program to give full servo movement (for example, to open/shut a vent).

Now that we have the PC controlling the servo, let's program some sequences of movements.

Automatic sequential movements using frames

The Pololu software can be used to program a sequence of movements, called 'frames'. The software can then be used to test and (if necessary) edit that sequence, before uploading the collection of frames (called a script) to the Maestro. If the script is configured to operate as a loop after switch-on, the Maestro will then act as a standalone controller (no PC connection needed), the sequence of servo events repeating until power is cut.

To achieve this programmed movement, go to the *Sequence* tab. The *Frame name* box will be empty at this stage, but you will be able to see that there are various editing tools and other controls available for manipulating the frames. To create the frames, go back to the *Status* tab – the one with the sliders. Set the position of the servo(s) for the first of the sequences of movement, then press *Save Frame 0*. Change the servo position and then press the *Save Frame* button again. Continue with this process until you have all your movements saved in a sequence of frames. Now return to the *Sequence* tab and you'll find the new frames listed there in order. Press *Apply Settings* and then when you press *Play Sequence*, the servo will make appropriate movements. If you tick *Play in loop*, the sequence will run continuously.

However, you might notice that some movements don't have enough time to be completed before the next one starts. To fix this, highlight a frame and then click on *Frame properties*. The time available for each frame can then be changed, with this time expressed in milliseconds, as shown in Fig.4.

Pressing *Copy sequence to script* and then, in the *Script* tab, *Apply Settings* lets you both see the code you've just created and upload it to the Maestro, respectively. This sequence of servo movements is now programmed into the module and can run continuously once power is applied, even without a PC connection. (Note: the speed and acceleration of all the movements in the sequence can be adjusted in *Channel Settings*.)

For sequences of movement, especially those that are repetitive like making a robot walk, this approach is fast and easy. But what if you don't want a pre-programmed movement sequence? Then you can use an external pot or switch to control the servo rotation.

External manual control

Let's now add a pot to give manual control over the servo position. First, a 2-pin header needs to be soldered into the GND and 5V out PCB holes. These then provide the two end connections to a 10kΩ pot, while the wiper connects to the input of one of the free channels (we will use Channel 5) – see Fig.5.

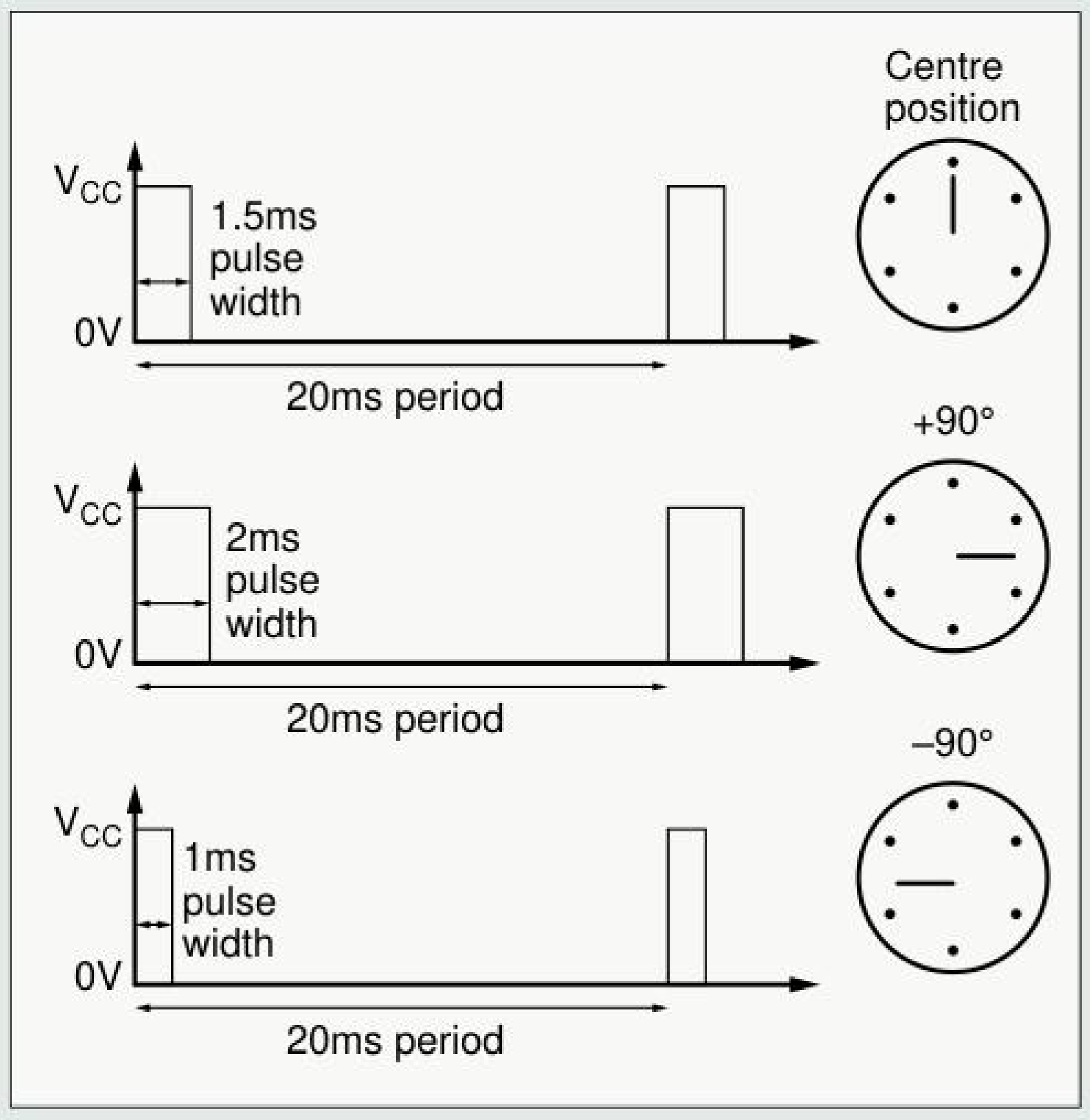
RC servos

RC (radio control) servos were developed for use in, not surprisingly, radio-controlled models. However, their versatility, low price and wide availability means that they're now used in a broad range of hobby activities.

Mechanically, a servo comprises a small DC motor connected to a geartrain, with the output shaft splined to take various levers and disks to which other linkages can be connected. A servo is a 'smart' device – it contains control electronics. An internal pot is used as a position sensor, and the motor rotates until the shaft reaches the required angular position. This position is then held – if the shaft is mechanically rotated from its set position, it actively resists.

Servos use three connections – power, ground and signal. The control signal comprises a pulse train with a varying pulse width 'on' time. It is not a PWM system with varying duty cycle, because the frequency of the pulses can vary over a wide range without affecting the servo's behaviour. (Standard frequency is about 50Hz – a 20ms period.)

The pulse width determines the servo's position, with 1.5ms corresponding to the servo's neutral point. That is, shorter pulse widths than 1.5ms causes the servo to rotate one way, and pulse widths longer than 1.5ms cause the servo to rotate the other way. The normal pulse width range is 1.0ms to 2.0ms, which corresponds to an output shaft rotation of up to 180° degrees (maximum – but in practice, often less than this).



Servo control signals use pulse width to control servo position. 1.5ms is the neutral position; shorter pulse widths rotate the servo in one direction and longer ones rotate it in the other direction. The full range is typically 1-2ms. The frequency of the pulse train can vary but is typically around 50Hz (a 20ms period).

Go to the *Channel Settings* tab and change the function of Channel 5 from *Servo* to *Input*. Now back on the *Status* tab, when you turn the pot, you should see the slider for Channel 5 moving to show the changing input signal (Fig.6).

To make the system use the pot to control the position of the servo, some scripting code is needed. However, this is just a few lines as shown below and in Fig.7:

```
begin
5 get_position
4 times 4000 plus
0 servo
repeat
```

Type this directly into the *Script* tab, tick *Run script on startup*, run the script and then press *Apply Settings* and the servo should move as directed by the external pot – and continue to do so, even when disconnected from the PC. Incidentally, if you wish to better understand the code, the PDF manual has a good explanation. For example, if you change the endpoints of the servo movement, you can change the pot scaling to suit, so that there's no dead travel in the pot's movement.

Even when controlled by a pot in this way, the maximum speed and acceleration of the servo can still be set by the previously described controls. It's therefore easy to give a progressive and smooth servo movement, even if the pot is turned quickly and/or jerkily.

To move over its full rotation, a switch can replace the pot. Pull the input up to 5V via a 1-100kΩ resistor and then use the switch to pull the input to ground – see Fig.8. Operation of the switch will now cause the servo to rotate from one extreme to the other – perfect for things that need to be open or closed, such as a vent. Again, this movement can be made to occur smoothly by using the *Acceleration* and *Speed* controls.

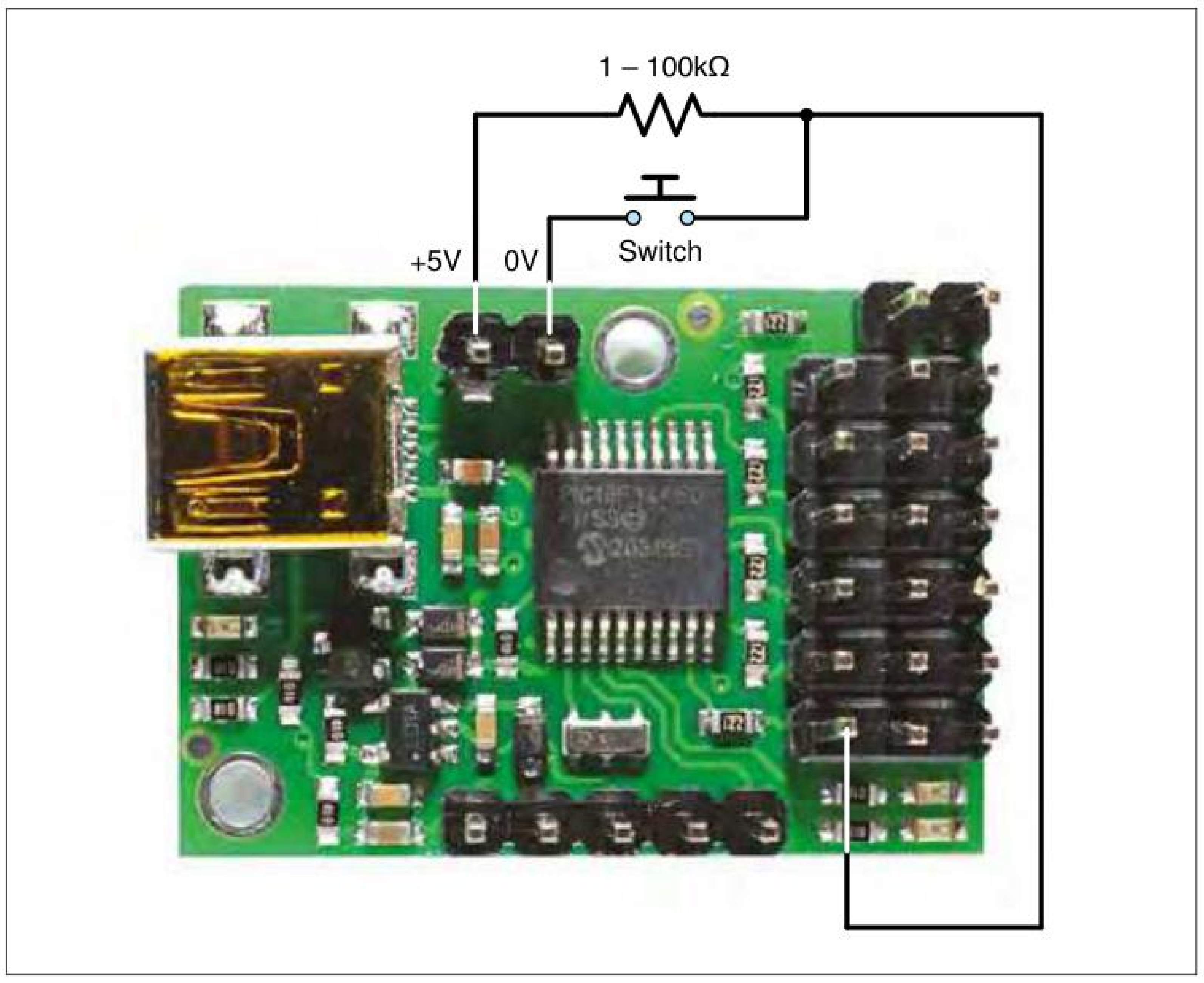


Fig.8. A switch allowing the servo to be set to two positions. The input is pulled up to 5V via the resistor when the switch is open; the input is pulled to ground when the switch is closed.

Conclusion

The Pololu Micro Maestro has a lot more capability than has been covered here (the manual is over 100-pages long). However, in this article I have been aiming at giving you fast and practical ways of controlling servos – methods than can be put into immediate effect. Whether that's opening and closing household vents, building a walking robot or even operating active aerodynamics on a car, the Micro Maestro and RC servos can help achieve all that.

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Advertisement offices
Matt Pulzer
Electron Publishing Ltd
1 Buckingham Road
Brighton
East Sussex BN1 3RA
Tel 07973 518682
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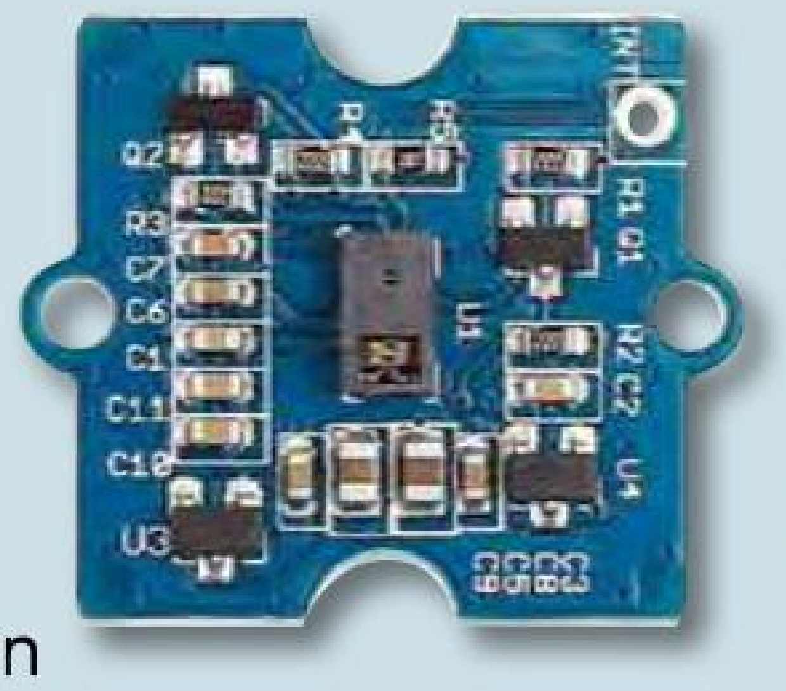
Next Month – in the June issue

Arduino Programmable Load

To test devices like power supplies, driver circuits and current sources, you often need a particular or variable load resistance that can handle a bit of power. This Programmable Load is based on an Arduino shield that is easy to understand, build and use. It can be controlled manually or automated in a way that suits your application.

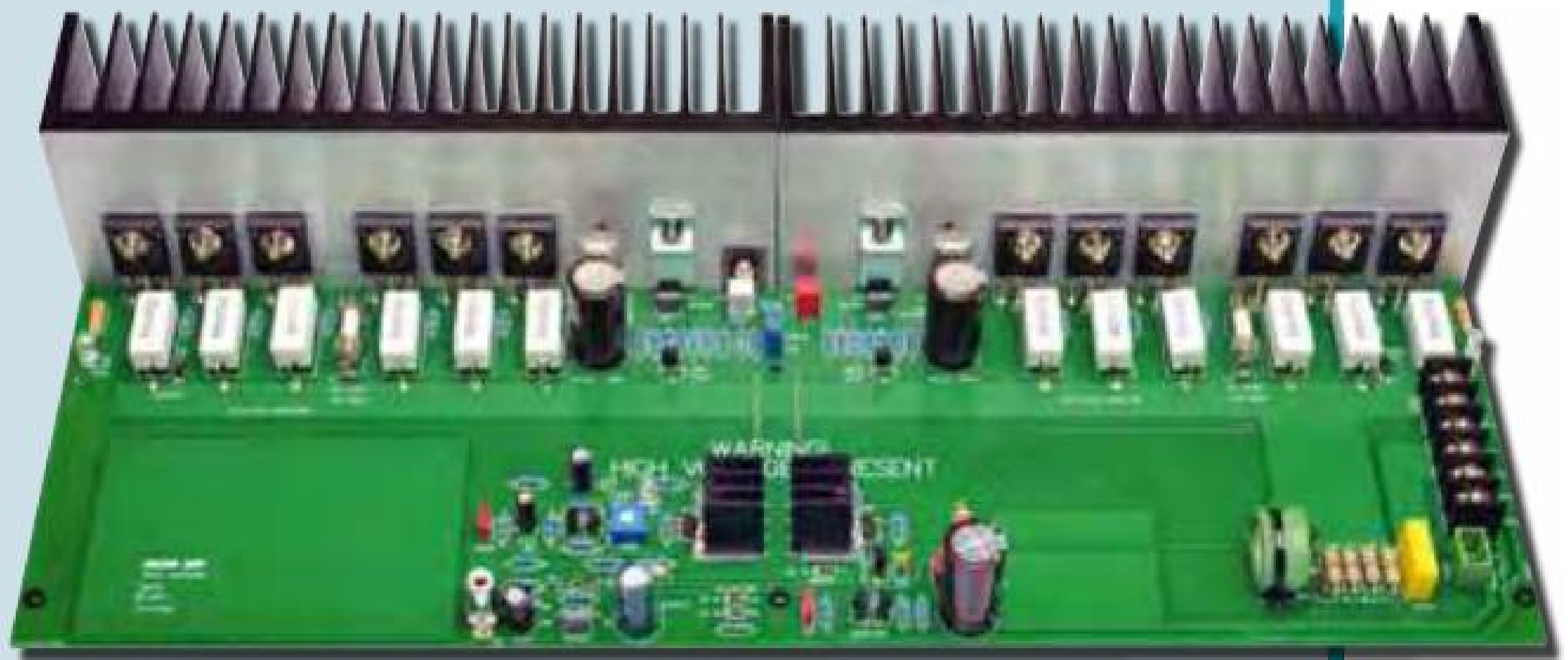


500W Power Amplifier – Part 3

To finish our new 500W Amplifier, we will describe the power supply configuration and the complete assembly details. That includes mounting all the modules and parts in the enclosure, wiring it up, checking that it works and making the calibration adjustments.

High-Power Buck-Boost LED Driver

We found some ridiculously bright, low-cost LED panels for sale, and then tried to figure out the best way to drive them. This Driver is the result; it is very flexible and useful for many other purposes, such as charging batteries from a DC source or converting between 12V DC and 24V DC.



CJMCU-7620 Gesture Recognition Module

With this module, you can experiment with sensing and recognising gestures made with your hands. It is very small, relatively low in cost and can easily be hooked up to an Arduino or a Micromite.

PLUS!

All your favourite regular columns from *Audio Out*, *Cool Beans and Circuit Surgery*, to *Make it with Micromite*, *Techno Talk* and *Net Work*.

On sale 4 May 2023

Content may be subject to change

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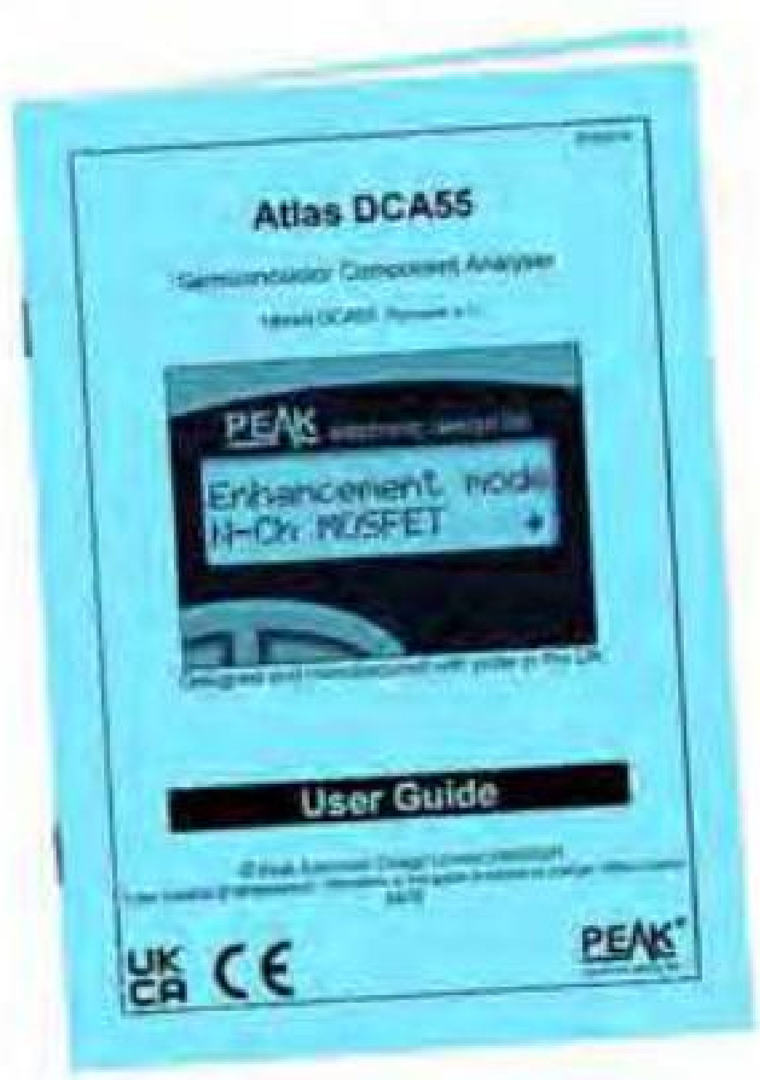

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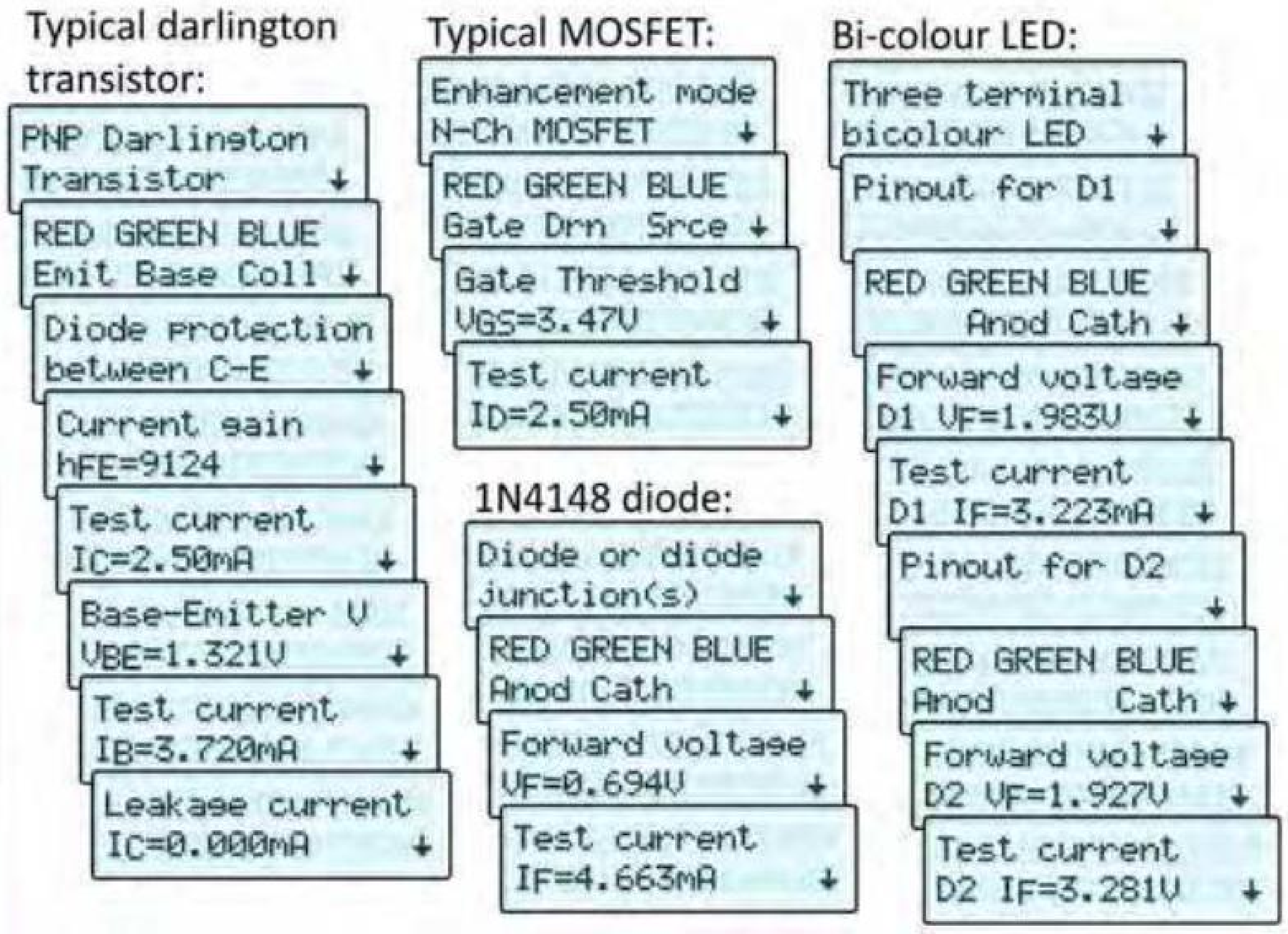
Example Screenshots



Typical darlington transistor:

```
PNP Darlington
Transistor     ↓
RED GREEN BLUE
Emit Base Coll ↓
Diode protection
between C-E    ↓
Current gain
hFE=9124       ↓
Test current
IC=2.50mA      ↓
Base-Emitter V
VBE=1.321V     ↓
Test current
IB=3.720mA     ↓
Leakage current
IC=0.000mA     ↓
```

Typical MOSFET:

```
Enhancement mode
N-Ch MOSFET    ↓
RED GREEN BLUE
Gate Drn  Srce ↓
Gate Threshold
VGS=3.47V      ↓
Test current
ID=2.50mA      ↓
```

1N4148 diode:

```
Diode or diode
junction(s)    ↓
RED GREEN BLUE
Anod Cath      ↓
Forward voltage
VF=0.694V      ↓
Test current
IF=4.663mA     ↓
```

Bi-colour LED:

```
Three terminal
bicolour LED   ↓
Pinout for D1
               ↓
RED GREEN BLUE
     Anod Cath ↓
Forward voltage
D1 VF=1.983V   ↓
Test current
D1 IF=3.223mA  ↓
Pinout for D2
               ↓
RED GREEN BLUE
Anod      Cath ↓
Forward voltage
D2 VF=1.927V   ↓
Test current
D2 IF=3.281V   ↓
```

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